GENERAL

THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

STACKING BEHAVIOR OF BOXES AND CORRUGATED BOARD

Project 1108-30

A Summary Report

to

FOURDRINIER KRAFT BOARD INSTITUTE, INC.

April 1, 1967

TABLE OF CONTENTS

	Page
SUMMARY	1
Box Stacking Life	1
Creep Life of Combined Board Columns	3
Relationship Between Box Creep and Column Creep	4
INTRODUCTION	6
Background Considerations	6
Materials	14
Box Creep Test Apparatus	14
Column Creep Test Apparatus	17
Column Creep Test Procedure	21
DISCUSSION OF RESULTS	24
Box Failure Time and Deflection *vs*. Applied Load	27
Relationship Between Log *a*, Board Properties and Box Dimensions	32
Relationship Between Log t, Board Properties and Box Dimensions	36
Comparison of Box Stacking Lives	43
Variability in Stacking Life	45
Relationship Between Box Creep Deflection and Failure Time	47
Creep Life of Combined Board Columns	53
Relationship Between Box Creep and Column Creep	69
LITERATURE CITED	85
APPENDIX. TABLE XVIII. RESULTS FOR BOXES UNDER TEST BETWEEN AUGUST 1 AND NOVEMBER 15, 1966	87
TABLE XIX. COVARIANCE REGRESSION LINE CONSTANTS FOR BOX RESULTS	88
TABLE XX. COVARIANCE TESTS OF RELATIONSHIP BETWEEN *R* AND BOX STACKING LIFE	89

THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

STACKING BEHAVIOR OF BOXES AND CORRUGATED BOARD

SUMMARY

This study was initiated for the purpose of studying factors affecting the stacking life of corrugated board and boxes. For this purpose top-loaded boxes from a number of A-, B-, and C-flute samples were subjected to a range of dead weight loads to determine the time-to-failure. Similar tests were carried out using short cross-direction combined board columns. This report summarizes results obtained in the study.

BOX STACKING LIFE

Interesting and unexpected results were obtained. Based on the literature it was expected that all boxes would exhibit about the same stacking life (aside from test variability) at the same load ratio (fraction of the short-term box compression strength). This was not the case. In general, the results indicated that:

1. There is a large and statistically significant difference in stacking life between the box lots studied. At a constant load ratio ($\underline{R}$) the box sample giving the highest stacking time exceeds the performance of the poorest sample by 30 or 40:1 as shown below.

Load Ratio	Stacking Life, days		
	Composite	Box 2408	Box 2457
0.75	7.3	1.5	43.1
0.70	22.0	3.4	130
0.625	113	22.7	666

2. The differences in box stacking life appear to depend in part on the perimeter and depth of the box as well as the combined board edgewise compression strength — and possibly other properties. In general, the lower the perimeter, the higher the stacking strength. Conversely, the higher the edgewise compression or box depth, the higher the stacking life. As is evident from 1, these factors may cause large differences in box stacking life. The effect of depth, in particular, seems contrary to what would be expected from the standpoint of engineering mechanics and should be regarded with caution. Because of the limited array of box sizes and constructions the relative importance of the various factors is somewhat uncertain. As a result the depth effect, e.g., may be overemphasized.

3. It is believed that factors such as perimeter, edgewise compression strength, etc., influence stacking life because they are related to the tendency for the panels to bow under load. This is termed creep buckling. If the degree of bowing is large, due to large panel sizes and low stiffness construction, the force required to hold the panel in the bowed form may be relatively low. This would shift a greater proportion of the total load to the vertical edges and result in shorter times to failure at the same applied load ratio, as compared to a box where little bowing occurs.

4. A number of statistical relationships were developed to relate stacking life to the applied load and other factors which were essentially equivalent in terms of multiple correlation coefficient. Two of these expressions are shown below:

$$\text{Log } t = -9.61R - 0.019Z + 0.014P_m + 0.060d + 7.6022$$

$$\text{Log } t = -9.30R - 0.646(Z/d)(Z/h)^{0.5}/P_m + 8.9618$$

where $\underline{t}$ = box stacking time, day

$\underline{R}$ = applied load ratio

$\underline{Z}$ = box perimeter, inch

$\underline{d}$ = box depth, inch

$\underline{h}$ = combined board caliper, inch

$\underline{P}_{\underline{m}}$ = C.D. edgewise compression, lb./in.

Thus, even at constant $\underline{R}$, two boxes may give quite different stacking lives depending on their dimensions and constructions.

5. These results are based on a small number of box sizes, flutes, and constructions. A limited study to help clarify the importance of the factors involved is under way.

6. The variability in box stacking life is large and seems to be explained by the variability in conventional box compression tests. Reductions in box compression variability would appear to be of significant importance to stacking strength.

CREEP LIFE OF COMBINED BOARD COLUMNS

The following trends were indicated by the results of creep tests on cross-direction short columns of combined board from which the abovementioned boxes were made:

1. The creep life (in logarithmic units) of short columns from the nine samples of combined board increased approximately linearly with decrease in load ratio in the range 0.75 to 0.625.

2. The column creep life at a given load ratio varied widely between the nine samples — by as much as a factor of four (based on smoothed data).

3. On the average, the creep life of the A-flute samples was higher than the C-flute samples of this study and the C-flute sample life was higher than the B-flute life; the effect of flute size was significant at the 0.01 level. While it is not unusual for the mechanical properties of combined board to be ranked in this order, the underlying reasons for the apparent effect of flute size on column creep life are unknown at this time. In view of the small number of samples in this study it is only tentatively concluded that flute size affects column creep life.

4. The average creep lives of the samples were ranked according to the series designation of the combined board in the following order: 200>350>175 >275. Physically plausible reasons for the above ranking are unknown, and it is doubted that the apparent effect of series is real.

5. It seems likely that the variation in short column creep life among samples at a given load ratio is attributable to some aspect of component behavior or a fabrication effect which is not reflected in the short-term column strength entering into the load ratio. Further study of this matter should be undertaken with the hope of learning ways to improve column creep performance and hence box stacking performance.

RELATIONSHIP BETWEEN BOX CREEP AND COLUMN CREEP

The relationship between box creep life and column creep life at the corresponding load ratio was studied. Among the conclusions which may be drawn are the following:

1. At a given load ratio, box creep life exceeded column creep life — by a factor of 10, on the average, for short-lived constructions and by a factor of three for long-lived constructions. The longer lives of boxes may be due to

(a) the greater structural complexity of the box structure and (b) the method of testing the short columns in this study which tends to underestimate average creep life of the sample.

2. Box creep life and column creep life (both in logarithmic units) were roughly proportional for a given sample.

3. For a given column life, there was considerable variation in box life among the nine samples. There was no strong evidence that the differences in box life were associated with flute size, series, or box dimensions, with the possible exception that depth or depth-to-perimeter ratio may be important.

4. Box creep life appears to depend on one or more box construction factors in addition to column creep life.

INTRODUCTION

The failure as a function of time of stacked boxes exposed to relatively constant loads during warehousing is a major use hazard for corrugated boxes. It is well known that a corrugated box subjected to warehousing stacking will support only a fraction of its short-term box compression strength for a prolonged period of time.

For this reason, a study was carried out to provide information relative to the stacking (creep) behavior of corrugated board and boxes. In the study the deflection and time-to-failure of top-loaded empty boxes were evaluated for a number of applied load levels expressed as a percentage of their short-term compression strength. Similar evaluations were carried out using short columns (cross-machine orientation) of corrugated board. All tests were carried out at 50% R.H. and 73°F.

Four preliminary reports were submitted to the Technical Division discussing various aspects of the results during the course of the study. This report summarizes the final results and conclusions reached in the study.

BACKGROUND CONSIDERATIONS

Paperboard is classified as a viscoelastic material. Its prerupture response to an applied load may include several types of deformation. These include (a) immediate elastic deformation, (b) delayed elastic deformations which are recoverable in reasonable lengths of time after removal of load, and (c) nonrecoverable deformations which are not recoverable in reasonable lengths of time after removal of load.

The relative importance of these types of deformation will depend to a considerable extent on the time scale of the event, environmental conditions, and other factors. For example, over long periods of time the delayed elastic and nonrecoverable deformations may be of greater significance than the elastic deformation. This is the case in warehouse stacking.

The usual laboratory compression test of empty or loaded boxes requires only a short period of time — normally, not over one or two minutes. Such "short-term" compression tests are of considerable utility; however, they require further interpretation when use conditions involve long periods of time under stress such as in warehouse stacking, etc.

If a small constant load is applied to a structural element for a period of time, a curve having the form shown in Fig. 1 will be obtained for nearly all materials. Thus, the responses of most materials to long-term loads are quite similar, though different mechanisms may be involved for dissimilar materials.

When load is applied, the initial deflection OA is obtained. This is usually considered to be instantaneous and is composed of elastic, delayed elastic, and plastic deformations.

In the primary stage of the creep curve, the rate of deformation continuously decreases. In the secondary stage the rate of deformation is approximately constant although less than in the primary stage. Although it is often treated as a straight line, it may actually be a very flat curve with a point of inflection when the rate of deformation begins to increase again. In the tertiary stage the rate of deformation increases and failure eventually occurs. Most mathematical treatments in the literature appear to be restricted to the primary and/or secondary stages of the creep curve because of the irreversible structural changes that may occur in the tertiary region.

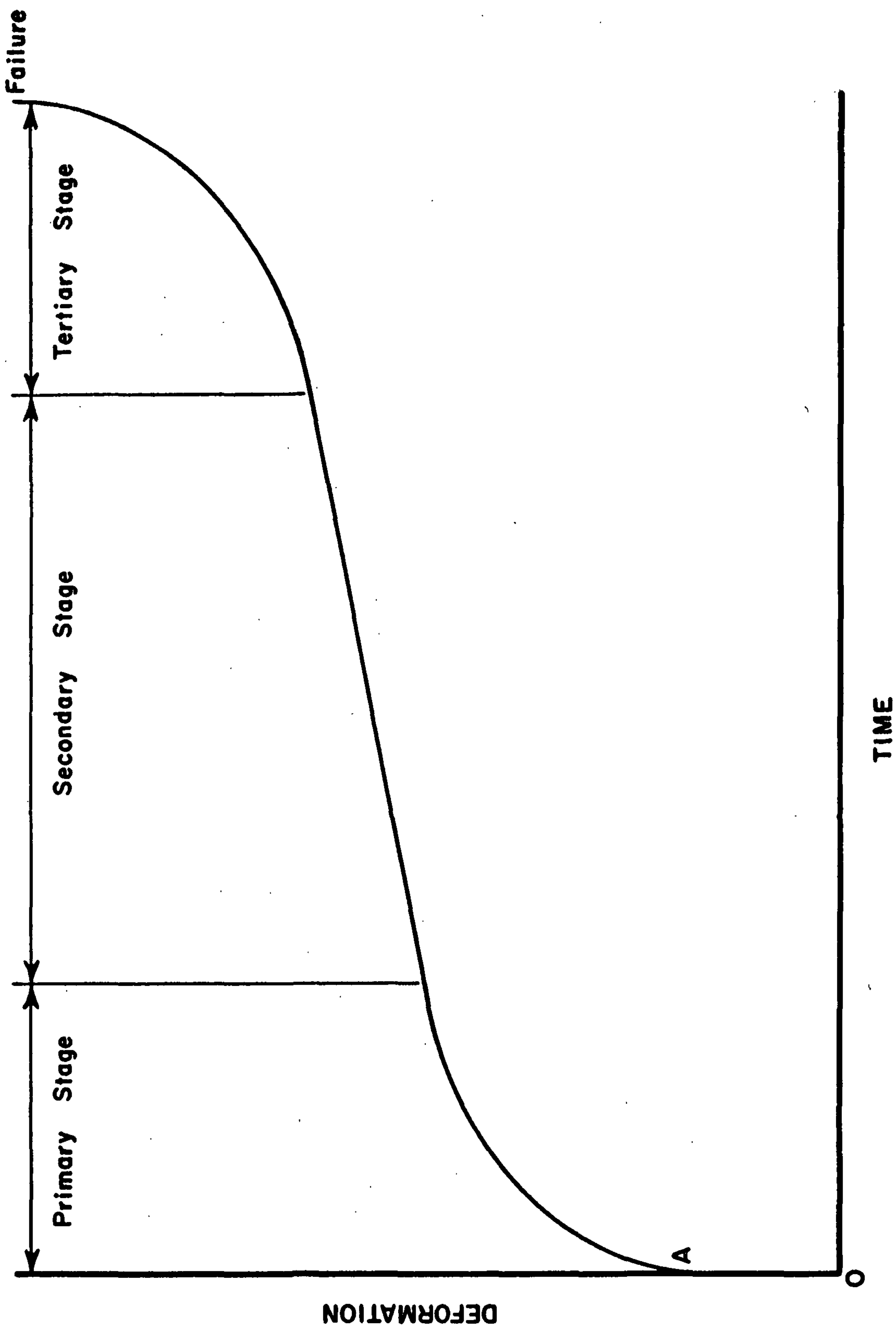

Figure 1. Idealized Creep Curve

The literature on the subject of creep is extensive and a complete review is beyond the scope of this study. Recent treatments of the creep of metals may be found in references (1-3). Alfrey has summarized much information on the creep behavior of high polymers (4).

The tensile creep properties of paper have been studied by a number of investigators. For example, Brezinski (5) carried out a comprehensive study of the creep behavior of paper. A portion of Brezinski's results are shown in Fig. 2. Brezinski found that at early times or low loads his results could be described in terms of the following equation:

$$y/L_o = Bt^a + c \tag{1}$$

where y = creep deformation, in. (first load)

L_o = initial specimen length, in.

t = time of loading, sec.

B, a, c = constants

At longer times (e.g., secondary stage) or higher loads, the deformation-time relationship became linear on a semilogarithmic plot and could be described by the following equation:

$$y/L_o = K_1 \log t + K_2 \tag{2}$$

where K_1 and K_2 are constants.

The many mathematical expressions used in the creep curve analysis of other materials are reviewed by Garofalo (1) and Clouser (6).

Rance (7,8) has presented tensile creep curves for paper at several constant loads. In general, the breaking load decreased linearly with the logarithm of the time of application. Similar results were obtained by Jacobsen (9) for paper and with cellulose films by Cheung (10). Busse, *et al*. (11) report

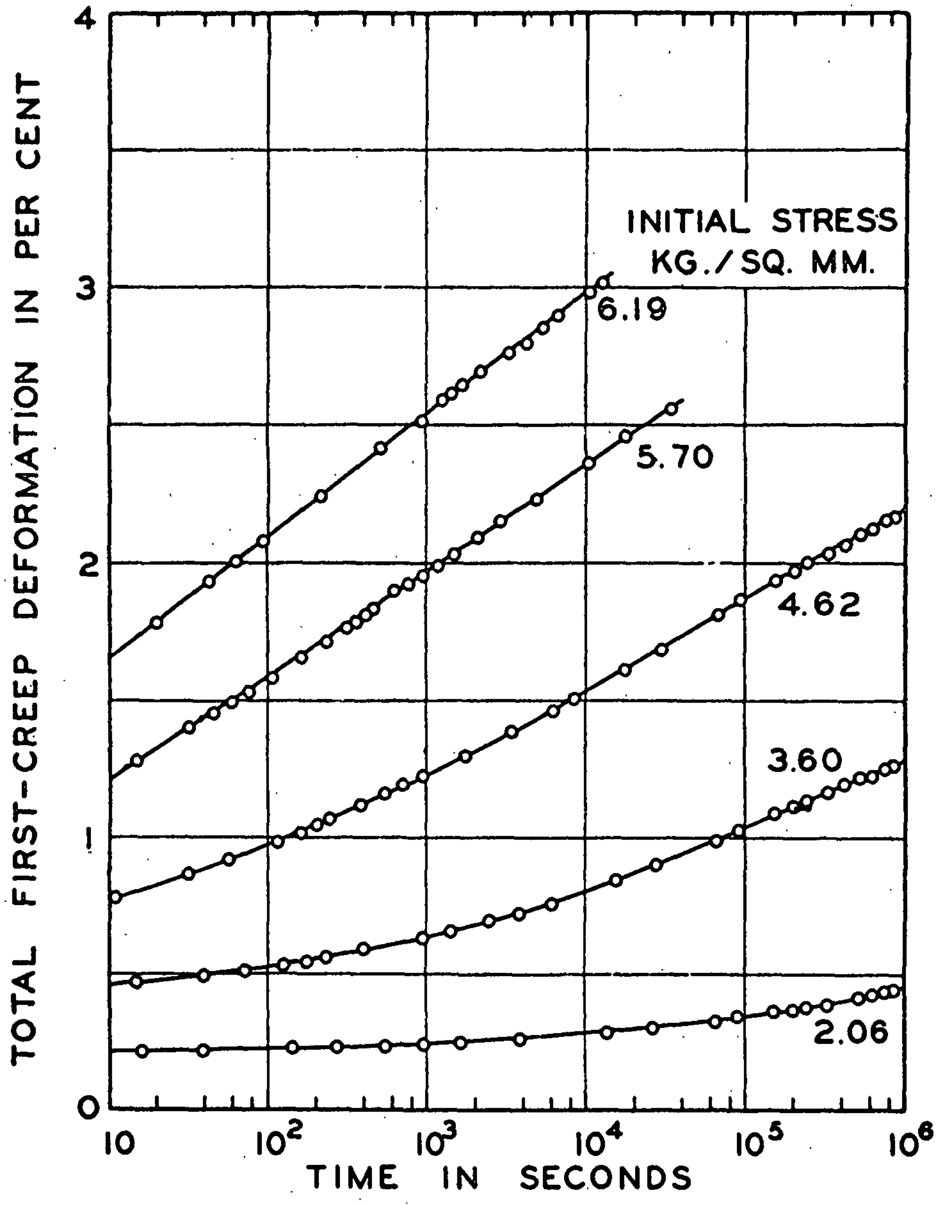

Figure 2. First-Creep Curves of Handsheet 23
(Brezinski)

similar results for cotton tire cords. Clouser (6) also obtained a semilogarithmic relationship between failure time and applied stress for wood beams.

There has been little published work relative to the creep characteristics of paperboard or boxes in compression. Kellicutt and Landt (12) studied the stacking life of empty corrugated boxes and found a semilogarithmic relationship between applied load and time for applied loads ranging between about 55 and 75% of the short-term compression strength. In a later paper Kellicutt (13) reported that filled boxes (shelled corn or plywood sleeves) gave longer lives than empty boxes. Brynhildsen and Dagel (14) studied the creep behavior of corrugated fiberboard tubes. The total creep deformation was related to time by means of the following equation:

$$Y_t = Y_o[1 + e_3 \log (t + 1)] \tag{3}$$

where Y_t = total unit deformation

Y_o = initial unit deformation

t = time

and e_3 = constant

It may be noted that when t is large, Equation (3) is similar to Equation (2).

Wolf (15) recently devised two nomographs based on the data by Kellicutt and Landt. Work on moisture and duration of load effects has also been done by Stott in Australia (16).

A recent paper by Moody and Skidmore (17) studied the relationship between creep rates in the primary and secondary regions and corrugated box stacking life. For boxes exhibiting relatively short stacking life the authors indicated that a "primary" creep rate defined in terms of Equation (2) decreased with survival time. However, it was felt that the variability in the relationship between primary creep rate and survival time was too great to permit use of the creep rate to predict survival time. The secondary creep rate also decreased with survival time over a range of box survival times from 100 to about 10,000 hours (4 days to about 400 days). However, the authors felt that further work would be required to use the secondary creep rate to predict failure life in view of the variability. Results were also presented indicating that (a) A-flute boxes gave longer lives than would have been anticipated from the B-flute data of Kellicutt and Landt (12) and (b) stacking lives at 50% R.H. and 73°F. were similar to those obtained at 80°F. and 65% R.H. provided the applied loads were equivalent ratios based on the short-term box compression tests in the respective conditions.

As noted, many of the above authors are in agreement that the logarithm of the time to rupture is linearly related to applied load for many materials — at least over certain ranges of applied load. In some areas of investigation, however, it is not uncommon to relate the logarithm of time to the logarithm of stress and much theoretical work is in progress to develop theoretical treatments of creep rupture for metals in particular (1,3).

If a constant load (less than the elastic buckling load) is applied to a column, Hoff (18) has shown that the column may become unstable and buckle after a finite period of time. Odqvist (3) presents an analysis of the creep behavior of a hinged end column with idealized H-section. Taking secondary creep into account and neglecting elastic deformations and primary creep, the analysis results in the following expression for time to buckling failure:

$$t = \ln\left[1 + 4/a_o^2\right] \Big/ 6\left[\frac{2b}{\pi h}\right]^2 \left[\frac{P}{A\sigma_c}\right]^n \qquad (4)$$

where $\underline{t}$ = time to buckling failure

$\underline{a_o}$ = initial deviation from straightness

$\underline{b}$ = half length of column

$\underline{h}$ = half thickness of column

$\underline{P}$ = applied load

$\underline{A}$ = cross-sectional area

$\sigma_{\underline{c}}$, $\underline{n}$ = material constants

It may be noted that the creep buckling time is dependent not only on the applied load but also on the dimensions of the column and its initial shape.

Creep buckling may be an important consideration in the creep life of corrugated boxes. As discussed by McKee, Gander, and Wachuta (19) most theoretical treatments of the short-term compression strength of corrugated boxes consider that the panels behave as thin orthotropic plates. When an increasing edge compression load is applied to a plate, the plate becomes unstable and buckles (bows) at a certain load. After buckling occurs the load continues to increase until failure which occurs when the compression strength of the material at or near the edges is exceeded.

Consequently, creep buckling can be a factor in plate behavior just as in a column. This may result in a complex dependence of time to failure on not only the applied load but also the box dimensions and other factors. Currently available results (discussed in the main text) appear to be in agreement with this hypothesis.

Hoff (20,21) has reviewed the literature pertaining to creep buckling. Gerard and co-workers have analyzed the creep behavior of plates (22,23). A review of these and other references is planned for future work.

MATERIALS

The box samples included in the study are identified in Table I together with the top-load box compression results and various combined board properties.

BOX CREEP TEST APPARATUS

Twelve sturdy tables were constructed with two test positions per table. A photograph of the apparatus is shown in Fig. 3. Table size was about 23 by 47 in. The top platens were made from three thicknesses of 3/4-in. plywood glued and screwed together to give high stiffness. Load was applied to the center of the platen by means of a rigid rod passing through the box and attached to a lever on the underside of the table. The rod applied load to the platen through load-leveling washers. The lever multiplying factors were approximately 10:1; the actual lever factor for each test position was experimentally evaluated using a Baldwin-Southwark Universal tester.

A dial gage mounted on a steel bar was used to measure deflection. Guide rods attached to each side of the table for each position supported the dial gage bridge rod.

The stepwise procedure used in carrying out the box creep tests is outlined below:

1. The box was placed on the table and the platen and guide rod were placed in position.

2. The heights of the side support rods for the deflection bar were adjusted to zero the dial indicator with the indicator bridge rod in a horizontal position.

TABLE I

BOX AND MATERIAL CHARACTERISTICS

Sample No.	Flute	Series	Dimensions, in. (l x w x d)	Joint	$\underline{Z}$, in.	Top-Load Compression: Load, lb. Av. ($\underline{N}$=10)	Top-Load Compression: Load, lb. Std. Dev.	Top-Load Compression: Deflection, in. Av. ($\underline{N}$=10)	Top-Load Compression: Deflection, in. Std. Dev.	Basis Weight, lb./M ft.^{2}	Caliper, in. ($\underline{N}$=10)	$\underline{P}_m$,[d] lb./in. ($\underline{N}$=10)	$\underline{D}_x$,[c] lb./in. ($\underline{N}$=10)	$\underline{D}_y$,[c] lb./in. ($\underline{N}$=10)	$\sqrt{\underline{D}_x\underline{D}_y}$ lb./in.	Flat Crush, p.s.i. ($\underline{N}$=10)
2406	A	200	16x12-1/4x9-1/2	Taped	56.5	940	47	0.59	0.0527	130	0.203	51.1	199	100	141	34.7
2407	A	200	21x17-1/2x19	Taped	77.0	975	41	0.64	0.0251	129	0.206	42.2	239	89	146	27.7
2408	A	200	23-1/2x23-1/2x19	Taped	94.0	1180	85	0.67	0.0327	131	0.206	45.7	213	98	144	31.4
2430	A	200	23-1/2x14x12	Taped	75.0	1060	75	0.61	0.0611	140	0.198	51.9	228	100	151	35.3
2456	A	175	13-1/4x6-5/8x12-1/2	Taped	39.8	555	37	0.44	0.0271	135	0.190	34.3	177	61	104	28.6
2457	C	350	12-1/4x12-1/4x19-13/16	Glued	49.0	1235[b]	98	0.93[b]	0.1657	351	0.192	74.4	266	134	189	39.1
2510	C	275	16x12x18-1/2	Stitched	56.0	960	49	0.45	0.0268	177	0.168	59.8	176	87	125	42.3
2497	B	200	15-3/8x10-1/4x11-3/4	Glued	51.2	665	37	0.38	0.0071	124	0.106[a]	45.9	60	27	40	35.2[a]
2498	B	275	17-7/8x16x11-3/8	Stitched	67.8	970	48	0.45	0.0288	176	0.125	63.5	117	52	78	45.8
2511	B	175	15-1/2x10-1/4x14-3/8	Glued	51.5	525	43	0.35	0.0233	116	0.113	39.6	61	24	39	43.3

[a]Average of tests in printed and unprinted areas.
[b]Multipeaked load-deflection curves.
[c]Strain rate = 0.0025 in./in./min.
[d]Strain rate = 0.025 in./in./min.

Note: Symbols
$\underline{Z}$ = perimeter
$\underline{P}_m$ = edgewise compression
$\underline{D}_x$, $\underline{D}_y$ = M.D. and C.D. flexural stiffness, respectively

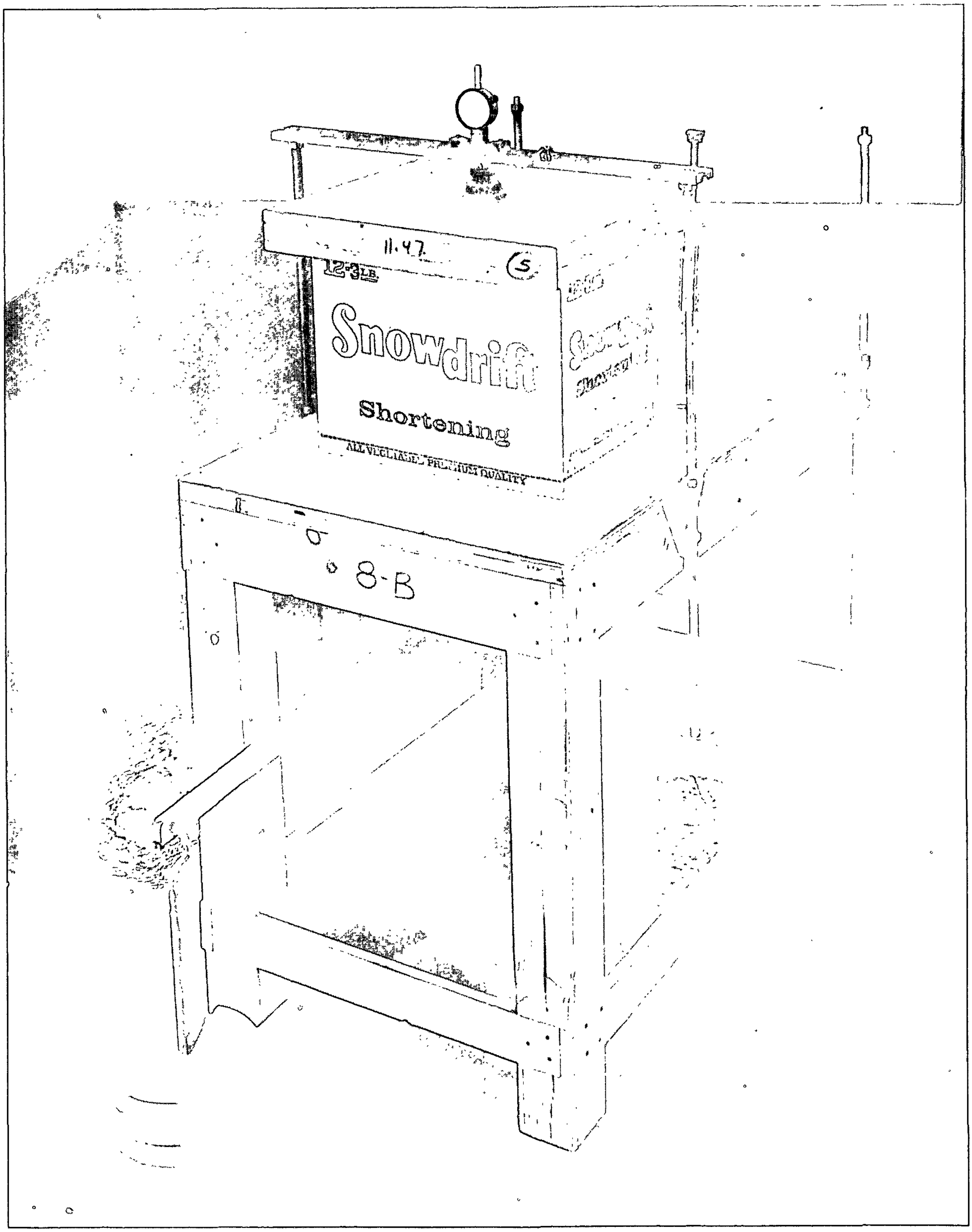

Figure 3. Box Stacking (Creep) Apparatus

3. A weight equal to 50 pounds including platen and hardware weight was applied to the box and the deflection was recorded after one and two minutes under load.

4. The appropriate weights were selected to give the desired load within ± 2 pounds.

5. A mechanical screw jack was inserted under the lever to hold it in its uppermost position.

6. The weights were hung on the end of the lever.

7. The screw jack was used to smoothly lower the lever to apply the load to the box. The application of load was complete in about 30 to 45 sec.

8. A timer was actuated at the first movement of the deflection dial indicator and deflection readings were usually taken at 1, 2, 10, and 60 min. after application of load. Additional deflection readings were taken at various intervals of time depending on the test duration – usually daily or twice weekly. The deflection at 50 lb. (Step 3) was subtracted from all deflections obtained under the test load.

9. A time clock actuated by a microswitch under the lever was used to measure time to failure for the boxes tested at the highest load ratio (0.75).

COLUMN CREEP TEST APPARATUS

The test device used to apply static loads to columns is shown in Fig. 4 and 5. These figures are photographs of the apparatus as set-up for testing. Figure 5 is a close-up view showing the details of construction.

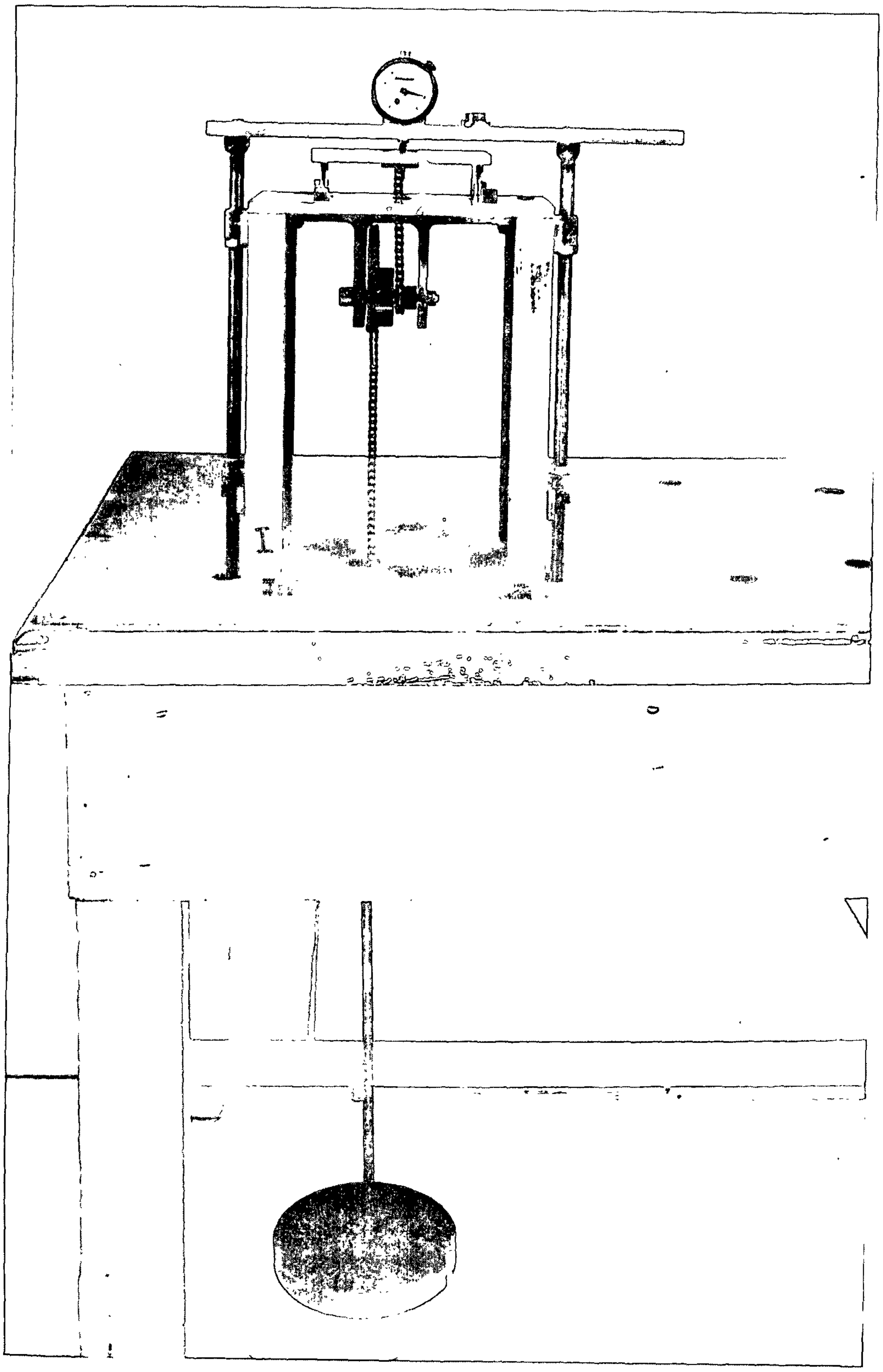

Figure 4. Column Creep Test Apparatus

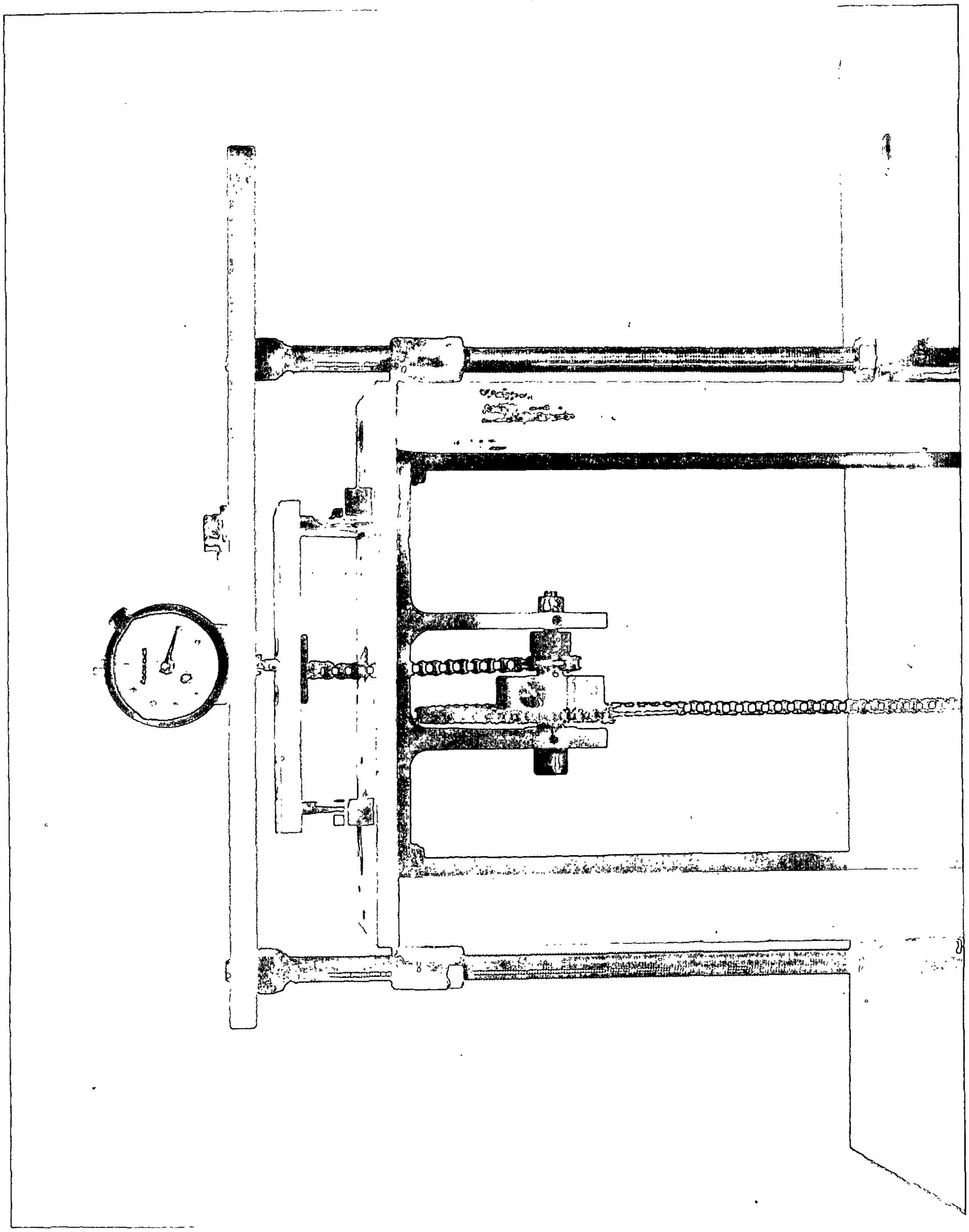

Figure 5. Column Creep Tester

The column creep tester is a small steel table with a 3/8 by 6 by 10-inch table top, standing 12-1/2 inches high on 1/4 by 1 by 1-inch angle-iron legs. The top of the table acts as the lower test platen.

Two specimens of combined board are tested simultaneously. The specimen height is 1-1/4 inches and the width is 2 inches. After the pair of test specimens is aligned on the lower test platen (table top), the upper platen (3/8 by 3 by 6-inch steel plate) is placed on top of the specimens and supported by them. The upper platen has a roller chain attached to it at midpoint, and this chain passes through an opening in the center of the table top and is wrapped around approximately two-thirds of the periphery of a small chain sprocket and fastened to it. A larger chain sprocket is also fastened to the same shaft. A chain is attached to and is wrapped approximately two-thirds of the way around the large sprocket. A weight pan is fastened to the chain on the large sprocket and weights are placed on the pan to load the specimens. The weights placed on the load pan exert a torque on the shaft, which is resisted through the upper platen by the pair of specimens in the tester. The chain sprockets are chosen so the differential between them gives the weights on the pan approximately a 5:1 mechanical advantage over the load supported by the columns. Six testers of the above design were used in this study.

The dial gage above the upper platen is used to measure deflection of the specimens with relation to time of test. The dial gage is mounted on a bar which rests on the top of two support studs and can be lifted off and replaced to enable measuring the deflection of more than one test.

COLUMN CREEP TEST PROCEDURE

The specimens were prepared for testing as described in Ref. (24). The edges were wax-treated and a column height of 1-1/4 inches was used for all flute sizes. Because it is necessary to test two specimens simultaneously between the same pair of platens, the specimens were prepared in matched pairs to minimize differences in height between specimens used for the same test set-up.

Location of the alignment blocks (1/2 by 1/2 by 1 inch) in relation to the upper platen was checked prior to each test. If the alignment blocks were not in the proper location or if a test table was being used for the first time, the blocks were placed at the proper location on the table top. Locating the alignment blocks was achieved by placing the upper platen on three (3) steel balls and letting the platen roll to a point of rest when the weight chain was pulled gently. After the upper platen had oriented itself to the line of pull, the alignment blocks were taped with double-face tape to the table top at each corner of the upper platen. The alignment blocks were located such that when the upper platen was set on the table top in orientation with its line of pull the 1/2 by 1/2-inch face of the alignment blocks would abut the long edge of the upper platen and the outer 1/2 by 1-inch face of the alignment blocks were in line with the short edge of the upper platen.

With the alignment blocks properly located on the lower platen (table top) the specimens were placed on the platen and positioned with the specimen alignment bar. The alignment bar for the specimens was placed on the lower platen so the outer face of the bar abutted the inner 1/2 by 1-inch face of the alignment blocks. A specimen was centered on the 1/8-inch projection of the bar which faced outward and was held in position and vertically aligned by a second alignment bar which was brought in contact with the outer face of the specimen. After both specimens were located, the upper platen, in orientation with its line of pull, was placed on top of the specimens and the alignment bars were removed.

With the specimens and upper platen in test position, the weight pan was hung from the chain attached to the large sprocket and weight was added to the pan to place a load on the specimen which did not exceed 25% of the total load to be applied. This preloading served to remove, at least in part, some of the deflection which might occur because of deformation of the loading edges of the specimens. When the deflection of the specimen remained sensibly constant — as noted by a dial gage suspended above the upper platen — a reading was recorded as the initial or zero deflection reading. Thereafter, the remaining weights required to load the specimens to the desired percentage of maximum load were gently placed on the weight pan, and a deflection reading was taken immediately after the addition of the weights. Deflection readings were made periodically throughout the lifetime of the specimen: on an hourly basis the first day of test, on a daily basis for short-term tests and on a semiweekly basis for long-term tests; more frequent readings were taken as the specimens appeared to approach the failure point.

At the conclusion of testing the failure time in days and the last measured deflection were recorded. Test times for long-term tests were on a basis of observed days. Test times for short-term tests were timed with an Intermatic time switch, Model T171, which was stopped when the upper platen tripped a Model B2-RWOX Microswitch as the specimens collapsed. Time was recorded as days or fractions thereof.

This test procedure is applicable to all rectangular shaped specimens. All A-flute samples in this study were tested as flat rectangular specimens. Rectangular specimens of B- and C-flute board, however, appeared to be unstable laterally, probably because of their lower caliper. The lateral instability of the B- and C-flute boards was overcome by placing a scoreline vertically at the center of the specimen using a slitter-scoring machine and folding the specimen to an "L" (or angle) shape prior to placing it in the tester. The same basic steps were used to test the "L"-shaped specimens as were used for flat rectangular specimens except that the specimens were positioned in the tester to support diagonally opposite corners of the upper platen. The "L" shape of the specimens was maintained by banding them with a rubber band; after the full load was placed on the specimens the rubber bands were cut with a sharp scissors and removed.

DISCUSSION OF RESULTS

The creep failure lives and deflections are shown in Tables II and III as of August 1, 1966. Tests in progress on August 1, 1966, were continued to November 15, 1966, at which time all tests were discontinued. The final results for these boxes are tabulated in Appendix I. Tests in progress on August 1 were omitted from the analysis with the exception of the three boxes from Sample 2457 at the load ratios (R) of 0.625 and 0.70. It was believed that the omission of the results for the three boxes concerned would bias the analysis of results for Sample 2457. As may be seen in Table II, the three boxes in question had survived for the following periods of time as of August 1: Box 3, 0.70R - 357 days; Box 4, 0.70R - 136 days; Box 2, 0.625R - 758 days. These values were used in the analysis. It may be remarked that the three boxes were still under test on November 15. Therefore, the use of the August 1 results for the three boxes in question were only a partial correction. If the tests had been carried to completion even longer average failure times would have been obtained for this sample.

Inspection of Table II reveals that there are wide differences in stacking life within a given sample at constant R. This is characteristic of creep failure life, in general. Such variations may be of practical importance since warehouse stacking complaints may originate because of the relatively poor performance of a few boxes in a given lot. This is discussed further in later pages of the text.

The large variability in stacking life is a complicating feature in any data analysis. One problem involves selection of the "best" way of averaging the data at a given R. Among the alternatives considered were (a) arithmetic

TABLE II

SUMMARY OF BOX CREEP RESULTS
(August 1, 1966)

Applied Load Ratio	Specimen No.	Failure Time, days									
		Sample 2406 A-200	Sample 2407 A-200	Sample 2408 A-200	Sample 2430 A-200	Sample 2456 A-175	Sample 2457 C-350	Sample 2497 B-200	Sample 2498 B-275	Sample 2510 C-275	Sample 2511 B-175
0.75	1	0.22	0.44	1.15		6.46	17.74	5.35[c]	0.89	4.88	1.49
	2	0.47	32.08	1.21		4.16	9.36	7.49	2.46	13.89	3.27
	3	0.50	15.49	1.39		0.03	26.10	0.25	3.11	50.60	4.78
	4	0.32	0.70	1.07		0.24	153.20	0.26	6.22	10.39	0.16[c]
	Av.	0.38	12.13	1.20		2.72	51.60	3.34	3.14	19.94	2.42
	L. Av.[b]	0.36	2.62	1.20		0.66	28.54	1.27	2.55	13.74	1.39
0.70	1	270.6	33.4		over 196	33.1	62.6	8.9	127.0	234.4	10.9
	2	19.6	40.6			132.7	243.2	53.8	15.9	over 136	3.6[c]
	3	20.0	41.7			79.5	over 357	9.5	35.7	49.1	10.3[c]
	4	4.5[c]	15.2			47.6[c]	over 136	4.0	35.2	over 73	18.6[c]
	Av.	78.7	32.7			73.2	199.7[a]	19.0	53.4	141.8	10.8
	L. Av.[b]	26.3	30.4			63.8	164.9[a]	11.6	39.9	107.3	9.3
0.675	1	30.5	87.9								
	2	62.1	76.4								
	3	38.4	222.4								
	4	20.4	over 141								
	Av.	37.8	129.0								
	L. Av.[b]	34.9	114.3								
0.625	1	33.8	15.8	16.5	29.8	115.4	72.6	19.9	248.3	320.7	62.6[c]
	2	4.8	13.6	79.6	62.9	167.4	over 758	7.7	160.4	81.7	63.0[c]
	3	155.7	95.9	13.1	90.1	655.9[c]	200.6	140.6	214.3	over 66	210.4[c]
	4	115.4	93.8	2.6	545.8[c]	577.9	405.8	101.5	263.0	over 53	246.7[c]
	Av.	77.4	54.8	28.0	182.2	379.2	359.2[a]	67.4	221.5	201.2	145.7
	L. Av.[b]	40.9	37.4	14.5	98.0	292.5	258.7[a]	38.4	217.6	161.9	119.6
0.575	1	over 479	over 479			over 659	over 659	315.9	over 669	over 348	202.4
	2					over 479		over 349			
0.55	1	113.3	366.6	129.3		over 756					
	2	114.5	387.4[c]	20.6		over 759					
	3	174.4	769.9	199.2							
	4	243.6		over 469							
	Av.	161.4	507.9	116.4							
	L. Av.[b]	153.2	478.2	81.0							
0.50	1		344.0								
	2		578.0								
	3		728.9								
	Av.		550.3								
	L. Av.[b]		525.3								

[a] Includes results for one or more boxes which have not failed.
[b] Average of logarithms of individual values.
[c] Failure along fingerlines.

TABLE III

COMPARISON OF BOX CREEP DEFLECTIONS PRECEDING FAILURE WITH MAXIMUM DEFLECTION IN THE BOX COMPRESSION TEST

	Deflection, inch									
	Sample 2406	Sample 2407	Sample 2408	Sample 2430	Sample 2456	Sample 2457	Sample 2497	Sample 2498	Sample 2510	Sample 2511
Max. deflection (box compression test), inch	0.59	0.64	0.67	0.61	0.44	0.93	0.38	0.45	0.45	0.35
Creep failure defl., inch[a]										
0.75 load ratio										
1	0.64	0.62	0.73		0.44	0.84	0.38	0.42	0.45	0.38
2	0.65	0.71	0.78		0.39	1.02	0.40	0.49	0.48	0.35
3	0.56	0.61	0.73		0.39	1.06	0.36	0.45	0.62	0.33
4	0.59	0.54	0.76		0.37	1.13	0.39	0.54	0.44	0.37
Av.	0.61	0.62	0.75		0.40	1.01	0.38	0.48	0.50	0.38
0.70 load ratio										
1	0.65	0.67			0.51	1.06	0.41	0.51	0.48	0.35
2	0.66	0.69			0.46	0.96	0.41	0.54		0.37
3	0.67	0.67			0.43		0.50	0.50	0.42	0.35
4	0.58	0.69			0.53		0.40	0.50		0.39
Av.	0.64	0.68			0.48		0.40	0.51		0.36
0.675 load ratio										
1	0.69	0.77								
2	0.66	0.70								
3	0.61	0.70								
4	0.54									
Av.	0.62									
0.625 load ratio										
1	0.63	0.67	0.62	0.61	0.44	0.99	0.38	0.58	0.51	0.33
2	0.63	0.56	0.77	0.68	0.49	--	0.38	0.48		0.36
3	0.70	0.68	0.74	0.61	0.52	0.95	0.43	0.52		0.40
4	0.66	0.64	0.76	0.69	0.53	1.05	0.42	0.52		0.39
Av.	0.66	0.64	0.72	0.65	0.49		0.40	0.52		0.37
0.575 load ratio										
1							0.44			0.36
0.55 load ratio										
1	0.60	0.63	0.78							
2	0.58	0.78	0.74							
3	0.54	0.68	0.76							
4	0.64									
Av.	0.59	0.70								
0.50 load ratio										
1		0.66								
2		0.74								
3		0.75								
Av.		0.72								
Comp. Av.	0.62	0.67	0.74	0.65	0.46	1.01	0.41	0.50	0.49	0.36
Ratio: $\frac{\text{Creep Deflection}}{\text{Box Deflection}}$	1.05	1.05	1.10	1.07	1.05	1.09	1.08	1.11	1.09	1.03

[a] The creep failure deflection is defined as the last recorded value of the box deflection prior to box collapse.

average, (b) logarithmic average, and (c) the median. Both the arithmetic and logarithmic (average of the logarithms of the individual stacking lives retransformed to time in days) averages are shown in Table II.

With such limited and perhaps, skewed data, the arithmetic average may be unduly influenced by extremely high or low test values. The logarithmic average should be less influenced by extreme values and may result in more symmetrical and more nearly normal distributions – an advantage in statistical work. As may be noted in Table II, the logarithmic average stacking lives were generally lower than the arithmetic averages. Both types of average have been utilized in various phases of the analysis.

BOX FAILURE TIME AND DEFLECTION *VS.* APPLIED LOAD

The arithmetic average creep failure lives for the boxes are graphed in Fig. 6 as a function of load ratio. The regression lines shown in Fig. 6 were obtained by fitting lines of common slope to the data for each sample using IBM covariance program 6.0.032. (Note: The differences in slope between samples were not statistically significant.)

The technique yielded equations of the following type:

$$\log t = \log a - 9.51R \tag{5}$$

where t = time, days

R = applied load ratio

a = a constant dependent on box sample – see Table XIX. Note: a corresponds to the intercept in a linear equation and is, therefore, a measure of the separation of the regression lines for the individual box samples.

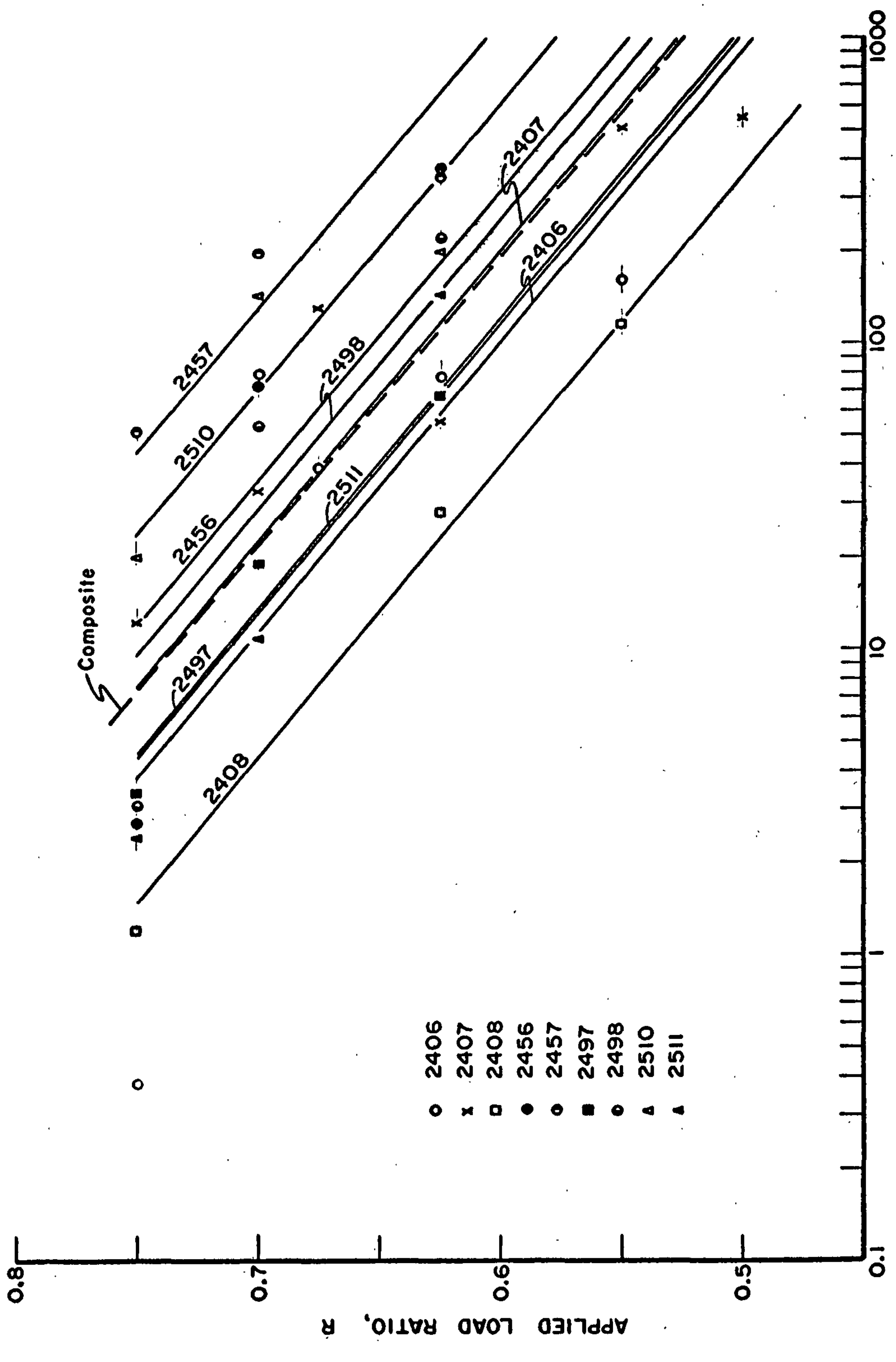

Figure 6. Relationship Between Box Failure Life and the Applied Load

As may be noted, Samples 2408 and 2457 differed most in stacking life. Using the curves shown in Fig. 6, the results in Table IV were obtained. The large differences in stacking life at constant R in Fig. 6 or Table IV are obvious.

The covariance analysis using the tests of significance described by Dixon and Massey (25), indicated that there were significant differences in life between the nine samples included in this study at the 0.025 level.

Similar covariance analyses were carried out using the logarithms of the individual values and the logarithmic average lives (see Table XX). Both analyses indicated that the differences in sample lives were statistically significant. However, using the individual logarithmic lives, the analysis indicated significant differences in regression line slope between samples and lack of linearity. Thus, fitting linear regression lines of common slope to the relationship between stacking life and R as in Fig. 1 could not be justified using the individual logarithmic stacking lives.

An analysis of variance (ANOVA) was also carried out at the 0.625, 0.70, and 0.75 load ratios using the data in Table II. The analyses were carried out using stacking times expressed in (1) days, and (2) transformed to logarithms. The logarithmic transformation is believed to be appropriate because (1) the logarithm of failure time is related to load ratio, and (2) the wide deviations in the individual data suggest that badly skewed distributions are present. As noted in Table V, the box samples of this study differ significantly in stacking life at all three load ratios in the logarithmic analyses. Even on the arithmetic basis, significant differences between samples were obtained at the 0.625 and 0.70 load ratios. This indicates that box stacking life is dependent not only on applied load but other factors as might be expected if creep buckling is involved.

TABLE IV

COMPARISON OF STACKING LIFE

Load Ratio	Composite	Stacking Life, day Box No. 2408	Box No. 2457	Kellicutt & Landt[a]
0.75	7.3	1.5	43.1	0.6
0.70	22.0	3.4	130	2.0
0.625	113	22.7	666	14

[a]From Reference (12).

TABLE V

ANALYSIS OF VARIANCE OF DIFFERENCES IN STACKING LIFE BETWEEN BOX SAMPLES

Source of Variance	Degrees of Freedom	Arithmetic Analysis Mean Square	F	Logarithmic Analysis Mean Square	F
		0.625 Load Ratio			
Between lots	8	67,730.0	2.44[a]	0.8239	3.46[b]
Within lots	27	27,730.0		0.2382	
		0.70 Load Ratio			
Between lots	6	16,396.0	3.01[a]	0.7314	4.18[b]
Within lots	21	5,441.0		0.1751	
		0.75 Load Ratio			
Between lots	8	1,100.1	1.86	1.9499	4.30[b]
Within lots	27	591.5		0.4531	

[a]Significant at the 0.05 level: $F_{0.05}$ (8,27) = 2.32; $F_{0.05}$ (6,21) = 2.58.
[b]Significant at the 0.01 level: $F_{0.01}$ (8,27) = 3.27; $F_{0.01}$ (6,21) = 3.82.

Therefore, the differences in failure life at constant R between samples may be dependent on the relative tendency for the box panel walls to bow under load. As bowing occurs, the load required to hold the central regions of the panel in a bent condition would probably diminish. This would transfer load to the vertical edges. Therefore, boxes with large panel walls which bow at relatively low loads might be expected to exhibit shorter stacking lives than boxes having small panel dimensions where little bowing occurs under load. The stiffness, flexural or compression, of the panel relative to its dimensions should also be a factor since the tendency of the panels to bow will be dependent on their material properties as well as dimensions.

As mentioned previously, a study of the literature relative to creep buckling is under way. Application of creep buckling theory to box failure should assist in delineating the important box dimensions and combined board properties which contribute to stacking life differences.

However, for this report the differences were statistically investigated to obtain preliminary indications regarding the significant box dimensions and combined board properties which might be involved.

The statistical analysis was carried out in two ways as follows:

In the first approach, the relationships between the intercept value log a in Equation (5) for the nine box samples and various board properties and box dimensions were studied. The log a values are a measure of the separation of the regression lines in Fig. 6 and give, therefore, an "averaged" ranking of the nine samples in terms of stacking life. One advantage is that the wide variability in the base data is smoothed out to a large extent allowing easier graphical examination of the results. The disadvantage is that since there are only nine samples and hence nine values of log a, there are few degrees of freedom available for multiple regression analysis.

In the second approach, the relationships between the logarithm of the average stacking life (log t) and various board properties and box dimensions were studied. This is, perhaps, a more direct approach than the log a analysis and the greater number of degrees of freedom is helpful on multiple regression analysis. For this reason the major statistical emphasis was placed on this approach. It should be kept in mind, however, that despite the apparent increase in degrees of freedom, the correlations still rest on only nine box samples.

Two procedures were employed in each approach. In the first procedure, a stepwise multiple regression program (IBM 6.0.032) was used to search out the best relationships between either log a or log t and various board properties and box dimensions. This type of program successively eliminates the least significant factors to produce favorable multiple regressions. While the variable elimination by the computer is automatic, careful judgment is required in assessing the results as in any multiple regression analysis. For example, highly intercorrelated variables can be a problem. In the second procedure, combinations of various board properties and box dimensions were correlated with either log a or log t.

Relationship Between Log a, Board Properties and Box Dimensions

An IBM stepwise regression program 6.0.043 was used to study the relationship between log a [see Equation (5)] and the following properties:

1. Perimeter, Z
2. Combined board, caliper, h
3. Combined board edgewise compression, P_m

4. Combined board flexural stiffness factor, $\sqrt{D_x D_y}$

5. Box depth, d

The following multiple regression was obtained:

$$\log a = 7.5917 - 0.0194Z + 0.0160P_m + 0.0518d \qquad (6)$$

In the above equation, Z was significant at the 0.025 level and P_m and d were significant at the 0.10 level. The multiple correlation coefficient was 0.91 indicating that the regression equation explained about 83% of the variation in log a, i.e., 83% of the variation in life between box samples. Equation (6) indicates that stacking life can be expected to

(1) increase as Z decreases

(2) increase as P_m increases

(3) increase as d increases

As P_m increases, or Z decreases, the tendency of the panel to bow should diminish. Therefore, if creep buckling is a factor in box life, increases in box stacking life might be expected. The inclusion of d as a significant factor in the regression was unexpected. Also, the implication that stacking life increases with increasing depth, other factors constant, is not readily explainable and should be viewed with caution. Because the correlations are based on a limited array of box sizes, the importance of depth may be overemphasized.

In addition to the above, various combinations of the above properties were studied to evaluate their effect on log a. The best relationships obtained are illustrated in Fig. 7 and 8. As may be noted, good correlations were obtained using the following equations:

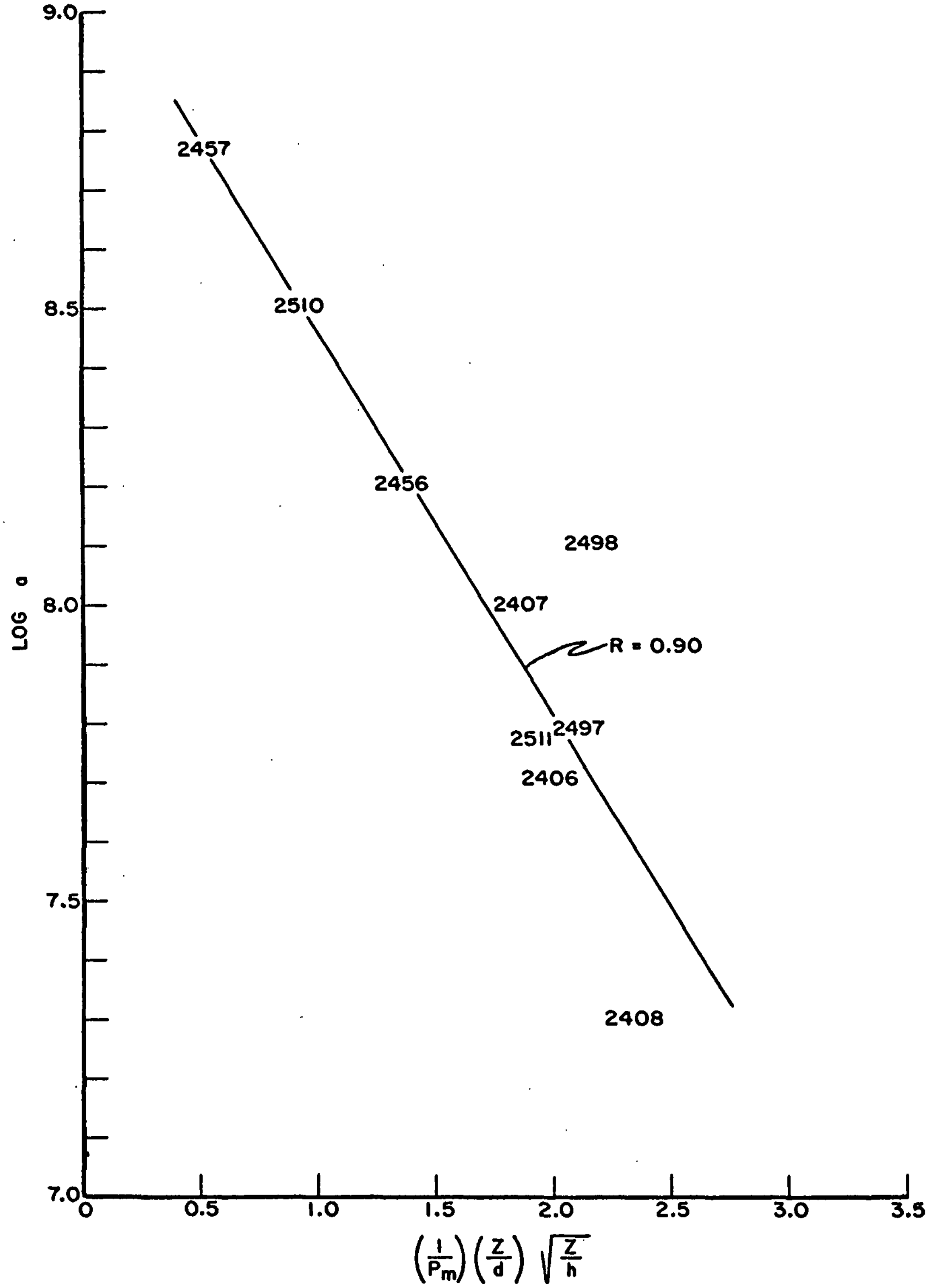

Figure 7. Relationship Between the Box Creep Life Intercept (Log a), Box Dimensions, and Edgewise Compression Strength

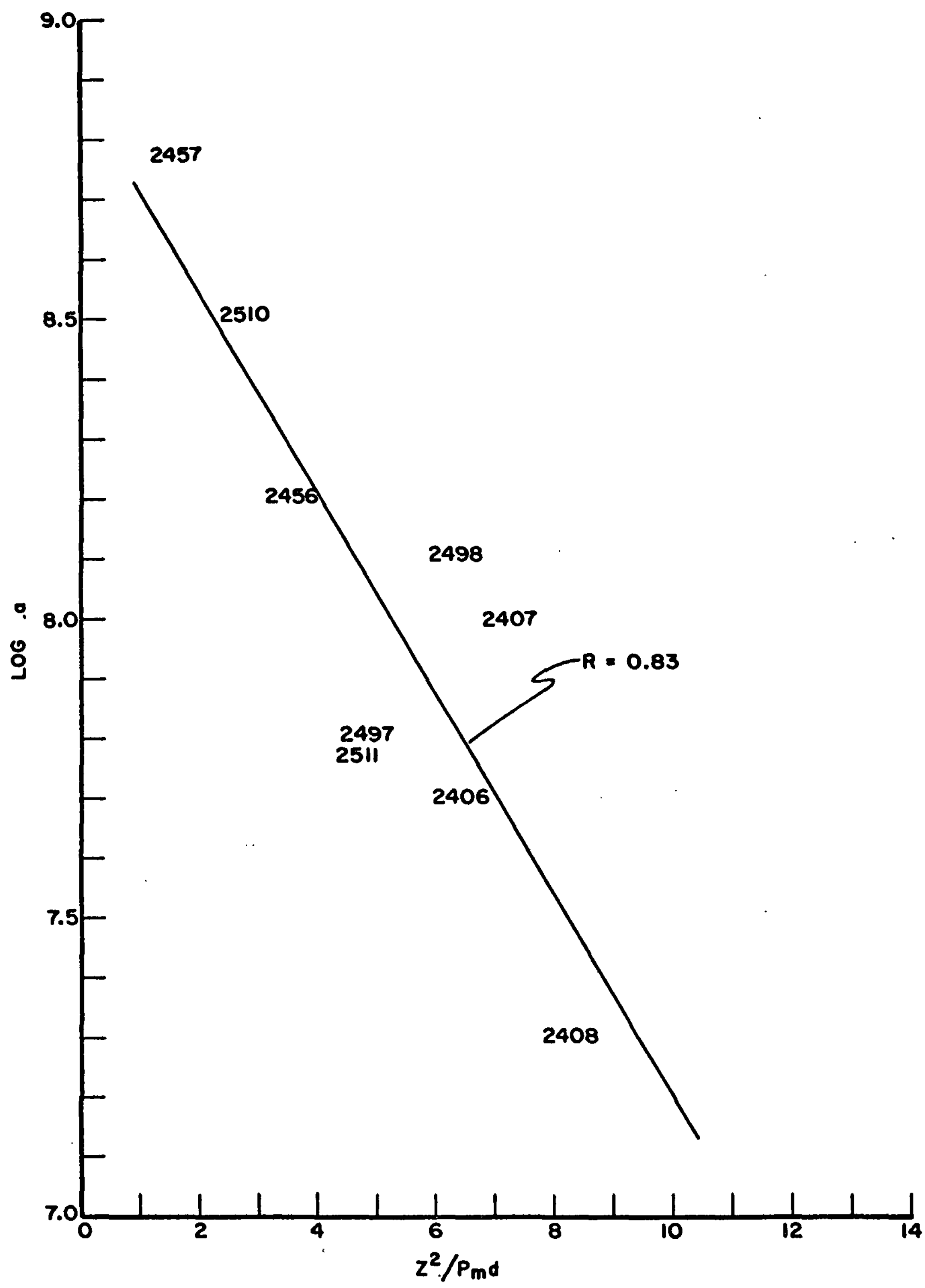

Figure 8. Relationship Between the Box Creep Life Intercept (Log a), Perimeter, Depth, and Edgewise Compression Strength

$$\log a = 8.878 - 0.168Z^2/P_m d \qquad (7)$$

$$\log a = 9.105 - 0.648(Z/d)(Z/h)^{0.5}/P_m \qquad (8)$$

where the symbols are as defined above.

These equations primarily differ in that Equation (8) incorporates caliper as an additional factor. Caliper is not believed to be a dominant factor; however, there may be some theoretical basis for its inclusion because it markedly influences bending stiffness.

Relationship Between Log t, Board Properties and Box Dimensions

To supplement the above analyses stepwise multiple regressions were performed using the box stacking life data in Table II. Among the factors included were perimeter, caliper, P_m, $\sqrt{D_x D_y}$, box deflection, box length, width and depth, applied load ratio (R), and various combinations of these factors. The best multiple regressions obtained are summarized in Table VI.

Equations (10) through (13) are about equivalent in terms of multiple correlation coefficient and the factors in each equation were statistically significant. Equations (10), (11), and (13) include the following factors in addition to R: perimeter (Z), P_m and box depth (d). On the other hand, the additional factors in Equation (12) are caliper, flexural stiffness, and the length-to-width box ratio. Additional theoretical insight coupled with additional data are needed to select among the several alternative factors and expressions. However, it seems clear that box stacking life is dependent on box dimensions and combined board properties in addition to the applied load.

TABLE VI

STEPWISE MULTIPLE REGRESSIONS
($\underline{N}$=32)

Equation No.	Regression Variables[a c]					"$\underline{F}$" Tests of Significance[b]				Fraction Explained Variance	Multiple Correlation Coefficient	$\underline{F}$
	Factor 1	Factor 2	Factor 3	Factor 4	Constant	Factor 1	Factor 2	Factor 3	Factor 4			
9	$-9.47\underline{R}$	$-11.0\ \underline{h}$	$+0.010\sqrt{\underline{D}_x\underline{D}_y}$	$+0.58\ \underline{d}/\underline{w}$	8.0209	62.76(.01)	5.55(.05)	6.60(.025)	7.31(.025)	.6646	0.815	28.74
10	$-9.61\underline{R}$	$-0.019\ \underline{Z}$	$+0.014\ \underline{P}_m$	$+0.060\ \underline{d}$	7.6022	70.73(.01)	10.21(.01)	4.20(.05)	7.14(.025)	.7524	0.867	20.51
11	$-9.64\underline{R}$	$-0.0078\underline{Z}^2/\underline{P}_m$	$+0.078\underline{d}$	--	7.5704	75.13(.01)	18.77(.01)	13.09(.01)	--	.7568	0.870	29.04
12	$-9.64\underline{R}$	$-23.1\ \underline{h}$	$+0.024\sqrt{\underline{D}_x\underline{D}_y}$	$+1.28\ \underline{1}/\underline{w}$	7.6138	71.18(.01)	17.71(.01)	21.59(.01)	10.69(.01)	.7586	0.871	21.21
13	$-9/60\underline{R}$	$-0.84\ \underline{Z}/\underline{P}_m$	$+0.065\underline{d}$	--	8.1593	72.63(.01)	17.48(.01)	10.05(.01)	--	.7502	0.866	28.03
14	$-8.56\underline{R}$	--	--	--	7.3603	38.88(.01)	--	--	--	.5645	0.751	38.90

[a] Regression form: $\text{Log } \underline{t} = \underline{a} + \underline{b}\underline{x}_1 + \underline{c}\underline{x}_2 \cdots \underline{r}\underline{x}_n$

[b] Level of significance in parenthesis

[c]

Symbols:	Factor:
$\underline{R}$	Load ratio
$\underline{h}$	Combined board caliper
$\sqrt{\underline{D}_x\underline{D}_y}$	Geometric mean flexural stiffness
$\underline{P}_m$	Edgewise compression
$\underline{l}, \underline{w}, \underline{d}$	Box length, width and depth, respectively
$\underline{Z}$	Perimeter

Taking Equation (10) at face value, Fig. 9 illustrates the separate effects of perimeter ($\underline{Z}$), edgewise compression ($\underline{P_m}$), and box depth ($\underline{d}$). It may be noted that stacking life increases (other factors constant) as

(1) perimeter decreases

(2) edgewise compression increases

(3) box depth increases

These are the same trends as obtained in the log $\underline{a}$ analysis. Reservations are held regarding the inclusion of depth as a significant factor in both analyses. It is hoped that additional data will clarify its importance as the correlations are based on a limited array of box sizes.

To supplement the above, two-factor multiple correlations were also performed using the box stacking life data in Table II. Various combinations of perimeter, depth, $\underline{P_m}$, and caliper were employed as second factors.

As may be noted in Table VII, the use of a second factor improved the multiple correlation coefficient — thus indicating that better predictions of average stacking life would be obtained. In many of the cases studied, the second factor is statistically significant at the 0.05 or 0.01 level.

The best correlations were obtained using Equations (16) or (17). These equations are shown below:

$$\log t = 9.0765 - 9.85R - 0.156Z^2/P_m d \qquad (16)$$

$$\log t = 8.9618 - 9.30R - 0.646(Z/d)(Z/h)^{0.5}/P_m \qquad (17)$$

where $\underline{t}$ = time, days, and the other factors are defined in Table VII.

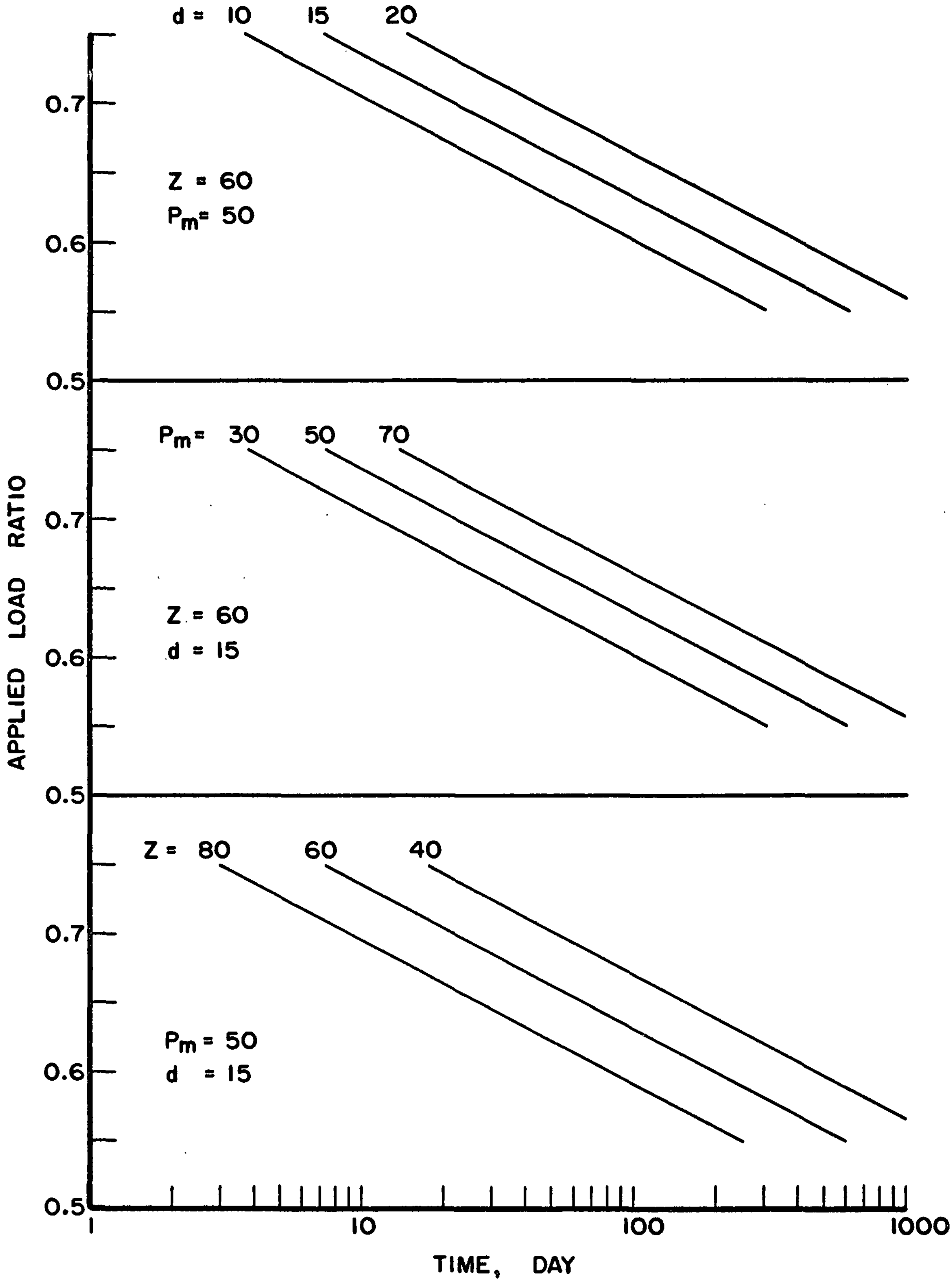

Figure 9. Effects of Perimeter (Z), Depth (d), and Edgewise Compression Strength (P_m) Box Stacking Life [Equation (10)]

TABLE VII

RELATIONSHIPS BETWEEN BOX STACKING LIFE, APPLIED LOAD AND OTHER FACTORS
(N=32)

Equation No.	Regression Constants[a,b] Factor 1	Regression Constants[a,b] Factor 2	Constant	"t" Test[d] Factor 1	"t" Test[d] Factor 2	Correlation Coefficient
15	$-8.57R$	--	7.3629	--	--	0.752
16	$-9.85R$	$-0.156Z^2/P_m d$	9.0765	8.30[c]	3.82(.01)	0.843
17	$-9.30R$	$-0.646(Z/d)(Z/h)^{0.5}/P_m$	8.9618	8.71[c]	4.66(.01)	0.867
18	$-8.62R$	$-0.00014Z^2/P_m h^2$	7.8177	6.78[c]	2.44(.05)	0.800
19	$-9.55R$	$-0.0048Z^2/P_m$	8.4280	7.21[c]	2.51(.02)	0.802
20	$-8.59R$	$-0.0624(Z/h)^{0.5}$	8.5702	6.50[c]	1.82(.10)	0.781
21	$-8.97R$	$-0.217Z/d$	8.5609	7.28[c]	2.95(.01)	0.816
22	$-8.79R$	$-0.019P_m$	6.6625	7.01[c]	2.47(.02)	0.800
23	$-9.35R$	$-0.000097Z^2$	8.2821	6.93[c]	2.13(.05)	0.790
24	$-9.33R$	$-0.013Z$	8.6508	6.86[c]	2.03(.10)	0.787
25	$-8.56R$	$0.201h^2$	7.3505	5.93[c]	0.024	0.752
26	$-8.50R$	$0.524h$	7.2246	5.91[c]	0.201	0.752
27	$-8.34R$	$0.034d$	6.6881	6.13[c]	1.42(.20)	0.770

[a] Regression Equation: $\log t = a + bR + cX$

[c] Significant at the 1% level.

[d] Level of significance in parentheses.

[b] Symbols	Quantity
t	Time, day
R	Applied load ratio
Z	Perimeter, in.
d	Box depth, in.
h	Combined board caliper, in.
P_m	Combined board edgewise compression, lb./in.

The equations primarily differ in that Equation (17) incorporates caliper as an additional factor. Caliper is not believed to be a dominant factor; however, there is some theoretical basis for its inclusion since it markedly influences bending stiffness.

Equation (17) is graphed in Fig. 10. At a given applied load ratio, $\underline{R}$ stacking life is shown at several arbitrary levels of the second factor – $\underline{M}$ = $(\underline{Z}/\underline{d})(\underline{Z}/\underline{h})^{0.5}/\underline{P}_{\underline{m}}$. Taking the equation at face value, stacking life varies with the quantities in the second factor as follows:

1. The lower the perimeter, the higher the stacking life.
2. The lower the caliper, the lower the stacking life.
3. The lower the value of $\underline{P}_{\underline{m}}$, the lower the stacking life.
4. The lower the box depth, the lower the stacking life.

The Institute understands that Kellicutt at Forest Products Laboratories has obtained longer stacking lives with double-wall boxes as compared to single-wall boxes. Also, Moody and Skidmore (17) indicated that A-flute boxes gave longer lives than the B-flute boxes evaluated by Kellicutt (12). Items 2 and 3, above, are in agreement with this result. The perimeter trend also seems reasonable at this time while the influence of depth seems more questionable as discussed previously.

The values of $\underline{M}$ in Fig. 10 for the boxes of this study ranged between about 0.5 and 2.5. The large differences in stacking life over this range, due to the box dimensions and combined board strength, are apparent. Double- or triple-wall boxes, if the dimensions were not large, might give lower values of $\underline{M}$ (less than 0.5) and correspondingly longer lives. This involves a considerable extrapolation of the present limited data.

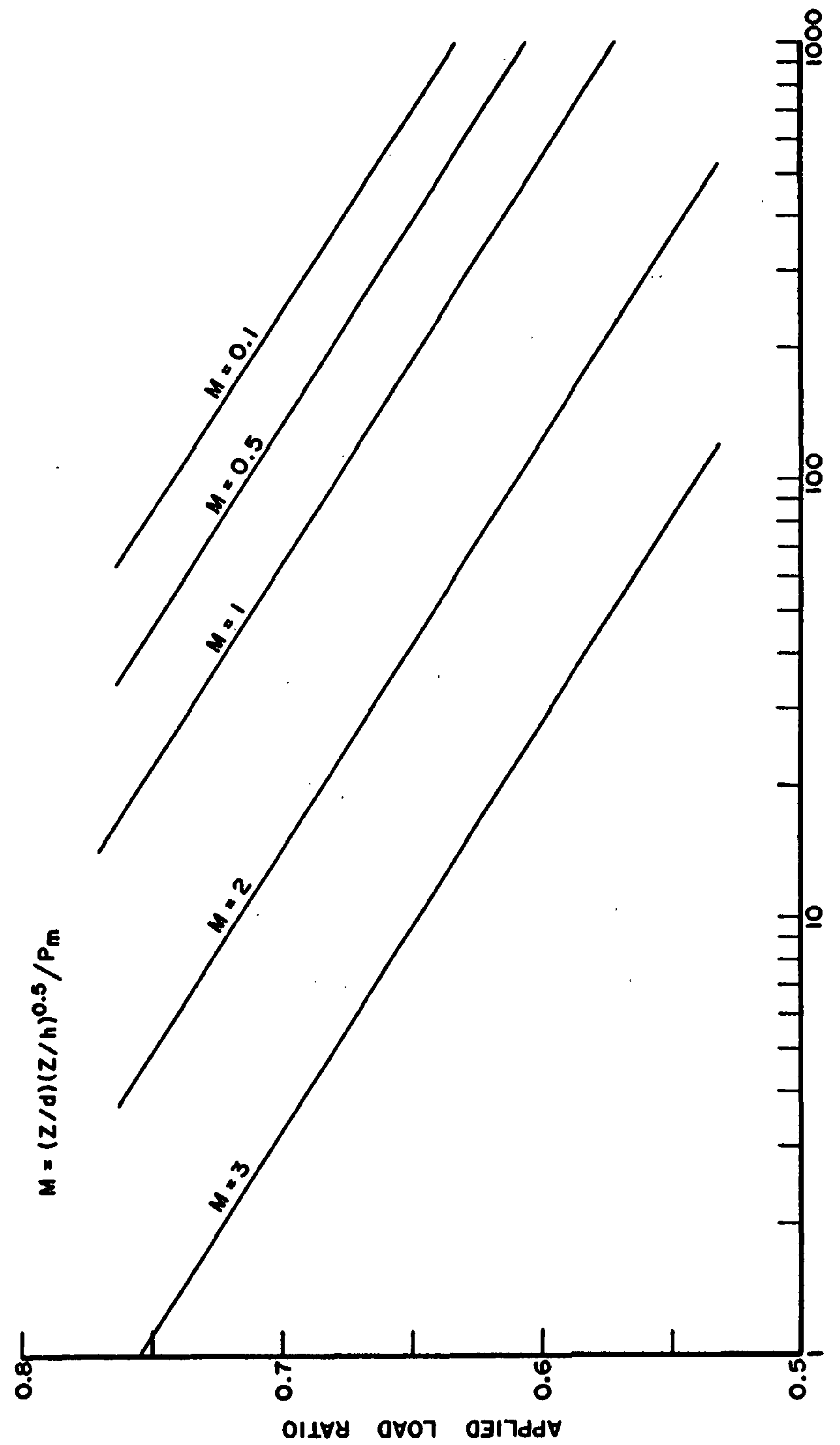

Figure 10. Relationship Between Box Stacking Life, the Applied Load, Box Dimensions, and Combined Board Properties

COMPARISON OF BOX STACKING LIVES

As mentioned previously, Kellicutt and Landt (12) and Moody and Skidmore (17) have published results for box stacking life. While it is difficult to directly compare the results of this study with the published work due to differences in box dimensions, combined board properties and test apparatus, a limited comparison is shown in Fig. 11. It may be noted that:

1. The composite relationship (based on the covariance analysis) for this study gave considerably longer lives than the original relationship derived by Kellicutt and Landt (12). Their work, however, was based on B-flute and solid fiber boxes, whereas the composite for this study includes A-, B-, and C-flute boxes. While no B-flute boxes for this study gave as short a life as would be expected from the Kellicutt relationship, the results of this study suggest that certain combinations of material properties and box dimensions may give results which would be comparable with the Kellicutt relationship.

2. With regard to the results obtained for A-flute board by Moody and Skidmore (17), it may be noted that the A-flute box sample (2408) giving the lowest life in this study exhibited lower average lives than the Moody relationship. Thus, the results of this study overlap the results given by Moody and Skidmore.

3. The small differences in slope between studies seem insignificant in view of the large variability in box stacking life.

4. Differences in data analysis may also contribute to apparent differences in life. For example, use of logarithmic averages in the covariance

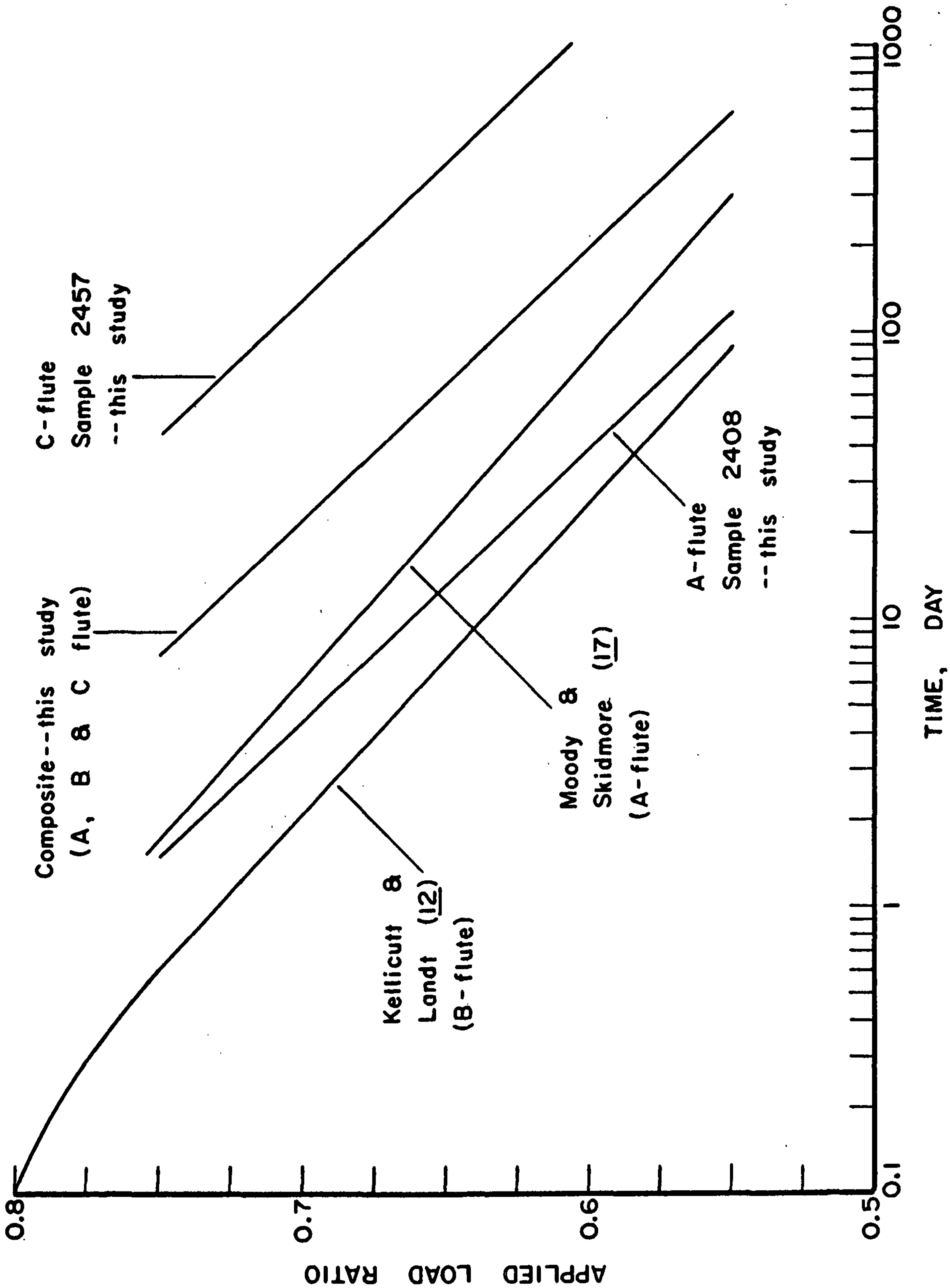

Figure 11. Comparison of Box Stacking Relationships

analysis for this study would probably tend to shift the relationships of this study toward shorter lives.

VARIABILITY IN STACKING LIFE

The above analysis was concerned with the differences in stacking life between box samples. The variation in stacking times within samples is also of practical importance, since warehouse stacking complaints may occur because of the poor performance of a few boxes in the lot. The effects of "normal" box variability on individual box survival time were estimated as follows:

1. Two standard deviation limits were computed for each box compression average. Approximately 95% of the individual box tests should be found within this range.

2. The applied load at the 0.625 load ratio was divided by the upper and lower two standard deviation load values to give upper and lower limits in the applied load ratio.

3. Stacking times at the upper and lower load ratios were read from the regression lines in Fig. 6.

The results are shown in Table VIII. As may be noted, the variability in box compression results permits a wide spread in load ratios. This can result in large differences in stacking time for individual boxes and appears to account for much of the variability in individual box stacking results. In practical applications, it appears that box variability alone would force use of a substantial safety factor in box construction to obtain satisfactory performance under a given loading. Whether this variability is inherent in the board or arises in the converting or boxmaking operation is an interesting question.

For example, glue skips might be one source of variability — in which case efforts to obtain more uniformity in gluing could produce a superior box.

TABLE VIII

BOX SURVIVAL TIME LIMITS BASED ON SHORT-TERM BOX COMPRESSION VARIABILITY

(0.625 Load ratio)

Sample No.	Load Ratios at at Two Standard Deviation Limits		Stacking Life, days		
			Av.	Max.[a]	Min.[a]
2406	0.568	0.694	58	200	12
2407	0.577	0.682	115	330	33
2408	0.546	0.730	23	130	2.3
2456	0.551	0.721	182	900	23
2457	0.539	0.743	666	3300	50
2510	0.567	0.696	357	1300	76
2497	0.562	0.703	70	280	12
2498	0.569	0.694	144	500	33
2511	0.537	0.747	67	460	4.8

[a]Read from Fig. 6 at the load ratios corresponding to ± 2 standard deviation limits.

During the course of the study the direction of bowing of the panels at failure was recorded. There seemed to be no readily discernible relationship between stacking life and the direction of bowing, i.e., in or out. Failure along fingerlines were observed in a number of instances — particularly in the case of Sample 2511. Failures along fingerlines were also observed for a number of other box samples; however, the stacking life for such boxes were not necessarily lower than boxes where failures along fingerlines were not observed.

RELATIONSHIP BETWEEN BOX CREEP DEFLECTION AND FAILURE TIME

During the box creep test, the deflection gradually increases with time. Failure occurs as the deflection nears the deflection attained in the box compression test (see Table III) with the important difference that deflection increases rapidly in the box stacking test as failure occurs.

An idealized representation is shown in Fig. 12. When load R_1 is applied the time to failure is long, although failure occurs as the critical deflection is reached. When a larger load, R_2 or R_3, is applied, failure occurs in a shorter time at about the same deflection level.

If it were possible to predict the path of a curve from data determined in short-term tests, failure time estimates could be made. In addition, if it were known that a given product would be damaged at some deflection less than the critical deflection, the time required to reach such deflections could also be estimated. Limited efforts were made to analyze the deflection *vs.* time creep curves from this viewpoint.

A series of deflection *vs.* time curves for Sample 2406 are illustrated in Fig. 13. The box data graphed were selected to have stacking lives near the average for the particular ratio. Preliminary trials indicated that curves of the type shown in Fig. 13 could be described by an expression of the following type:

$$\log t = \log K_1 + K_2 \log (D - D_o) \tag{28}$$

where t = time

D = deflection

and K_1, K_2, and D_o are constants

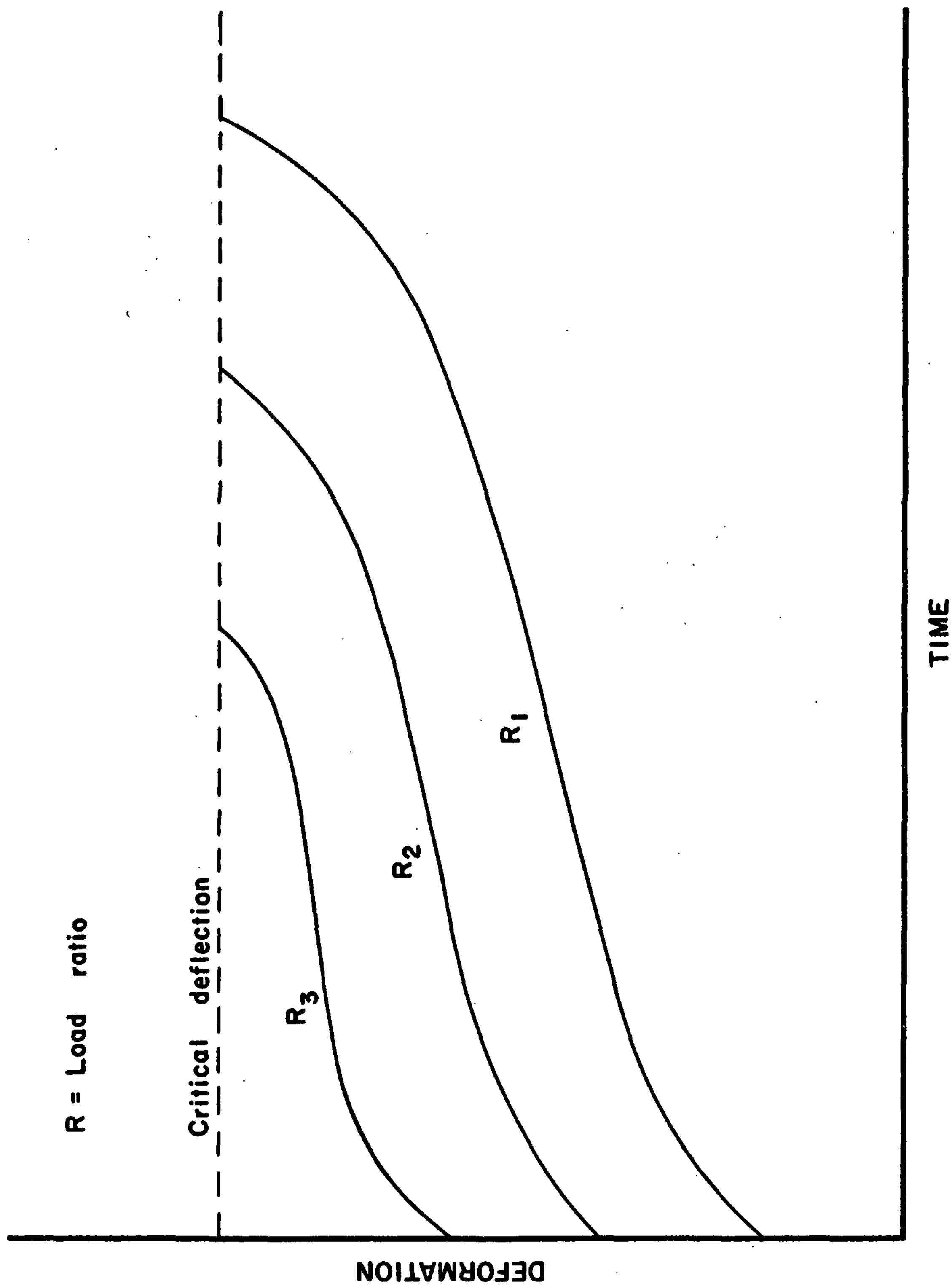

Figure 12. Idealized Box Deflection vs. Time Curves

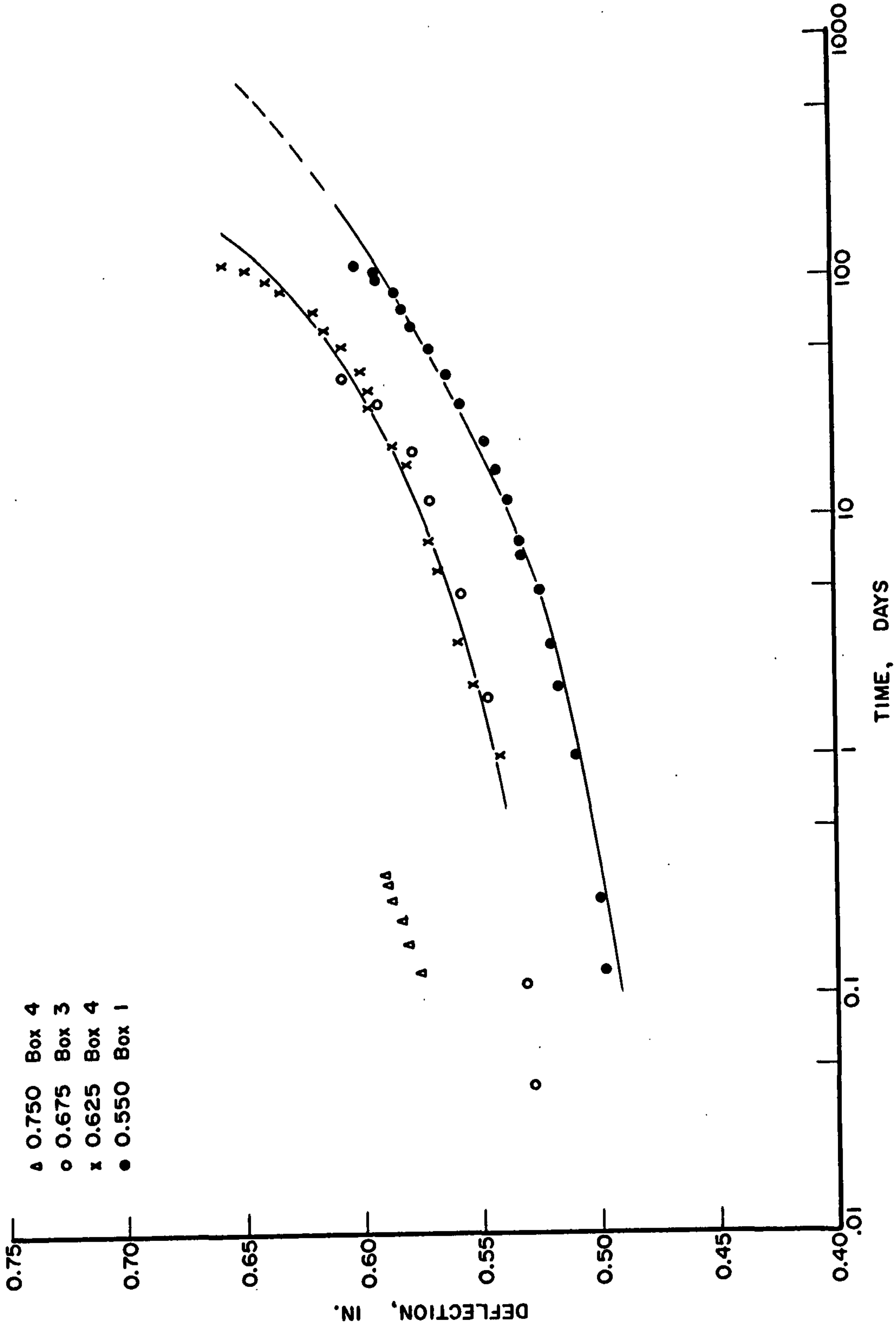

Figure 13. Creep Deflection vs. Time Curves for Sample 2406

Reasonably good fits to the creep curves (neglecting time values less than 0.1 day and negative values of $D-D_o$) were obtained by setting D_o equal to the deflection at 60 minutes (D_6). Typical regression lines are shown in Fig. 14. To be useful, however, the regression constants must be constant for most board constructions or must vary in some predictable manner with the applied load ratio and short-term tests.

In this connection, D_6 is a measure of the initial deformation and should be related to the applied load ratio and the maximum deflection (D_f) in the conventional box compression test. To investigate this possibility, the box deflections at 60 minutes were divided by D_f and graphed *vs.* the load ratio as shown in Fig. 15. It is evident that the relationship between these quantities was only fair. The regression line had a correlation coefficient of 0.67 and its equation was as follows:

$$D_6/D_f = 0.259 + 0.917R \tag{29}$$

where D_6 = box deflection at 60 minutes

D_f = box deflection at failure in short-term box compression test

R = applied load ratio

To investigate the utility of this approach, the stacking results for Sample 2406 were investigated in detail. Using Equation (29), predictions of D_6/D_f were made for each load ratio and D_6 was calculated. These values of D_6 were then used to obtain regression equations having the form of Equation (28) for each box at each load ratio. In addition, at each load ratio, a composite regression equation (CRL) was obtained as well as an equation obtained using a covariance technique (CVL).

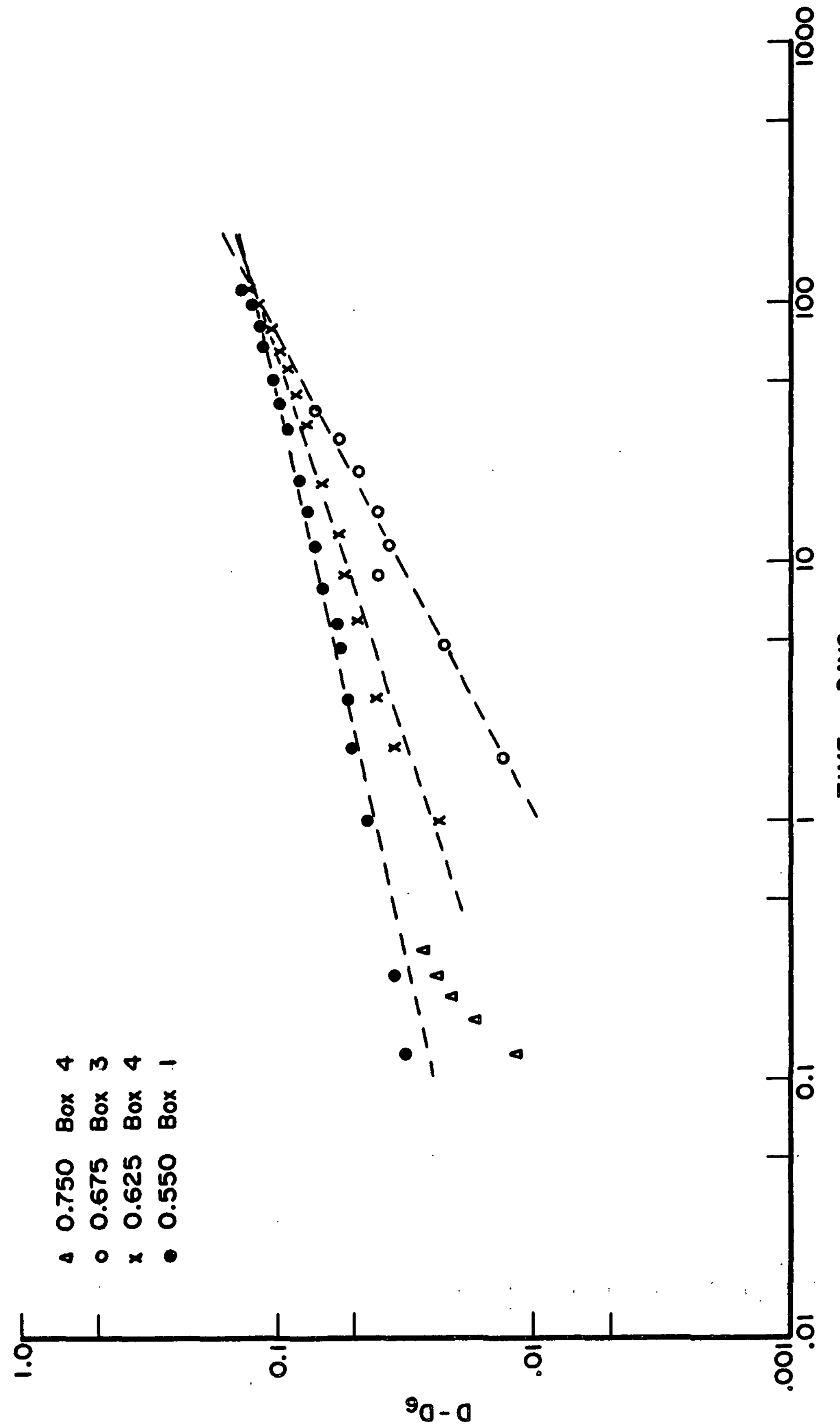

Figure 14. Relationship Between Box Creep Deflection Difference and Time for Sample 2406

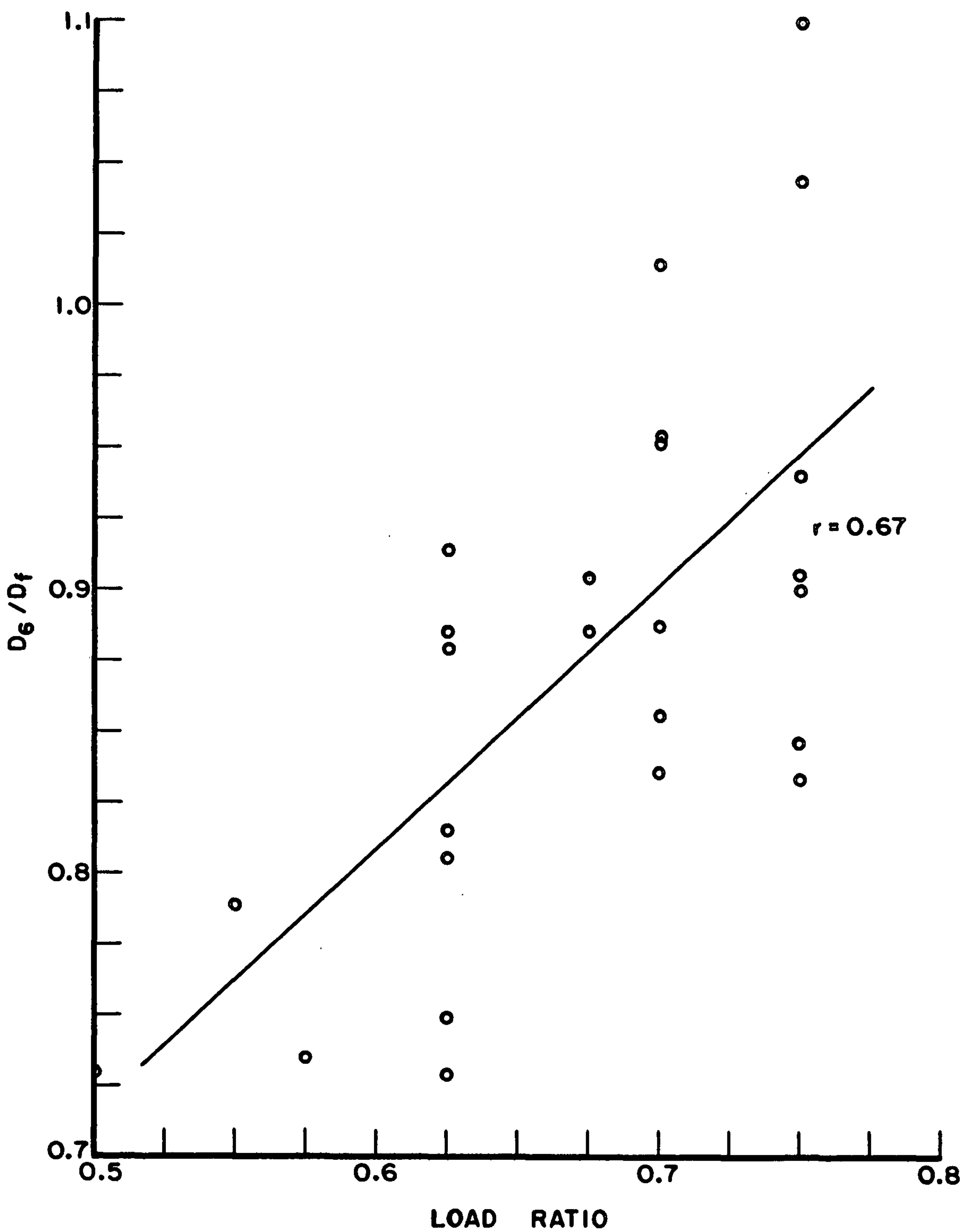

Figure 15. Relationship Between $\underline{D_6}/\underline{D_f}$ and the Applied Load Ratio

The results are shown in Table IX. It may be noted that at constant load ratio, the constants varied widely from box-to-box. Predictions of failure life were also quite poor though they could be improved by an upward adjustment of the critical box deflection reflecting the somewhat greater creep deflections near failure (see Table III).

The wide variability in box failure life complicates this approach. For this reason the work was halted and other possible functions were not investigated.

CREEP LIFE OF COMBINED BOARD COLUMNS

The creep life of short columns (cross-direction) was evaluated for the nine samples of combined board at load ratios $\underline{R}$ = 0.625, 0.70, and 0.75. Analogous to the box creep tests, $\underline{R}$ is the ratio of applied load to the edgewise compression strength of the combined board as evaluated in a short-term compression test.

The results of the column creep tests are given in Table X in terms of failure time (creep life) in units of days. The averages shown in the table are arithmetic averages. It may be noted that there is high variability between column specimens within a sample at a given load ratio, as is characteristic of creep data in general.

The relationship between average creep life and load ratio for each sample of board is shown graphically in Fig. 16; life is plotted on a logarithmic scale, as in the analogous graphs for boxes (Fig. 6). The three points for a given sample of combined board are connected by line segments. In a gross sense, creep life increases with decreasing load ratio, $\underline{R}$, as would be anticipated.

TABLE IX

DEFLECTION VS. TIME REGRESSION EQUATIONS FOR BOX 2406

Identification	D_6	N[a]	Regression Constants[b] Intercept	Regression Constants[b] Slope	R	Stacking Life, days: Observed Max.	Observed Min.	Observed Av.	Predicted	Diff.
				0.55 Load Ratio						
Box 4-1	0.450	44	3.89079	1.49979	0.986	--	--	174.4	408	+223.6
Box 1-2		46	6.71057	5.41464	0.983	--	--	113.3	122	+ 8.9
Box 2-3		46	5.17188	3.32442	0.980	--	--	114.5	215	+100.5
Box 3-4		69	5.40790	3.87065	0.980	-	--	243.6	127	-116.6
Comp. reg. line (CRL)		205	2.94983	1.28458	0.524	243.6	113.3	161.4	71	- 90.4
CRL minus box 4-1		161	4.93890	3,37269	0.903	243.6	113.3	161.4	115	- 46.4
Covariance line (CVL)		205	4.97052	3.08069	--	243.6	113.3	161.4	173.8	+ 12.4
				0.625 Load Ratio						
Box 1	0.491	26	4.13399	2.82496	0.989	--	--	33.8	19.8	- 14.0
Box 2		7	4.18915	3.94868	0.985	--	--	4.8	1.7	- 3.1
Box 3		59	5.55217	4.25109	0.970	--	--	155.7	19.2	-136.5
Box 4		35	5.61961	4.27143	0.983	--	--	115.4	21.4	- 94.0
CRL		127	5.00488	3.70517	0.904	155.7	4.8	77.4	19.2	- 58.2
CVL		127	4.95838	3.65839	--	155.7	4.8	77.4	20.0	- 57.4
				0.675 Load Ratio						
Box 1	0.518	11	4.96835	4.22860	0.947	--	--	30.5	1.4	- 29.1
Box 2		20	5.66631	4.49324	0.973	--	--	62.1	3.4	- 58.7
Box 3		13	4.98382	3.10574	0.989	--	--	38.4	27.2	- 11.2
Box 4		3	--	--	--	--	--	20.4	--	--
CRL minus box 4		44	3.53418	2.27633	0.759	62.1	20.4	37.8	8.6	- 29.2
CVL minus box 4		44	5.04474	3.70696	--	62.1	20.4	37.8	6.4	- 31.4
				0.700 Load Ratio						
Box 1	0.532	108	5.18213	2.89072	0.976	--	--	270.6	40.5	-230.1
Box 2		9	7.28515	6.52166	0.975	--	--	19.6	0.2	- 19.4
Box 3		10	7.84542	7.49984	0.973	--	--	20.0	0.04	20.0
Box 4		2	--	--	--	--	--	4.5	--	--
CRL minus box 4		127	3.60316	1.64519	0.374	270.6	4.5	78.7	37.0	41.7
CVL minus box 4		127	5.17684	3.10612	--	270.6	4.5	78.7	21.7	57.0

[a] The number of data points after discarding negative values of $D - D_6$ and time values less than 0.1 day.

[b] Regression equation: $\text{Log } t = \text{Log } K_1 + K_2 \text{ Log } D - D_6$.

TABLE X

CREEP LIFE OF COMBINED BOARD COLUMNS

Applied Load Ratio	Specimen No.	Failure Time, day								
		Sample 2456	Sample 2406	Sample 2407	Sample 2408	Sample 2510	Sample 2457	Sample 2511	Sample 2497	Sample 2498
		A-175	A-200	A-200	A-200	C-275	C-350	B-175	B-200	B-275
0.75	1	1.06	1.41	0.17	0.16	0.02	0.79[a]	0.05	5.18[a]	1.08
	2	3.55	0.31	0.05	0.52	0.48	0.95[a]	0.60	0.05[a]	0.11
	3	0.08	1.51	0.16	7.01	0.06	0.33[a]	0.01	0.04	0.13
	4	0.07	0.07	5.57	0.13	8.65	0.03	0.12	0.10	6.06
	5	0.36	1.01	0.62	0.18			0.07	0.08	0.10
	Av.	1.02	0.86	1.31	1.60	2.30	0.52	0.17	1.09	1.50
0.70	1	8.19	14.61	3.42	21.17	8.39	1.03[a]	0.44	0.30[a]	0.13[a]
	2	4.00	6.75	3.63	1.37	1.02	9.44[a]	4.47	6.90[a]	0.02
	3	25.92	1.99	6.34		0.09	0.45	1.86	0.71	1.17
	4			9.49		0.02		1.55	1.54	0.02
	5			2.98		37.01		0.01	0.99	1.82
	Av.	12.70	7.78	5.17	11.27	9.31	3.64	1.67	2.09	0.63
0.625	1	30.75	20.38	12.30	26.64	30.97	45.97[a]	2.58[a]	99.08[a]	1.71
	2	98.99	85.56	46.70	40.97	3.02	56.63[a]	223.04	15.59[a]	5.00
	3	27.64	22.08	6.83	219.49	1.63	28.97[a]	2.06	8.42[a]	6.34
	4	46.10	4.39	6.05	10.64	10.31	241.36[a]	20.24	69.55	69.18
	5	92.03	11.07	14.44		5.98	13.66[a]			
	6	120.56		23.37						
	7			7.79						
	8			14.44						
	Av.	69.34	28.70	16.49	74.44	10.38	77.32	61.98	48.16	20.56

[a] Tested as rectangular column whereas other C- and B-flute samples tested as angle specimens.

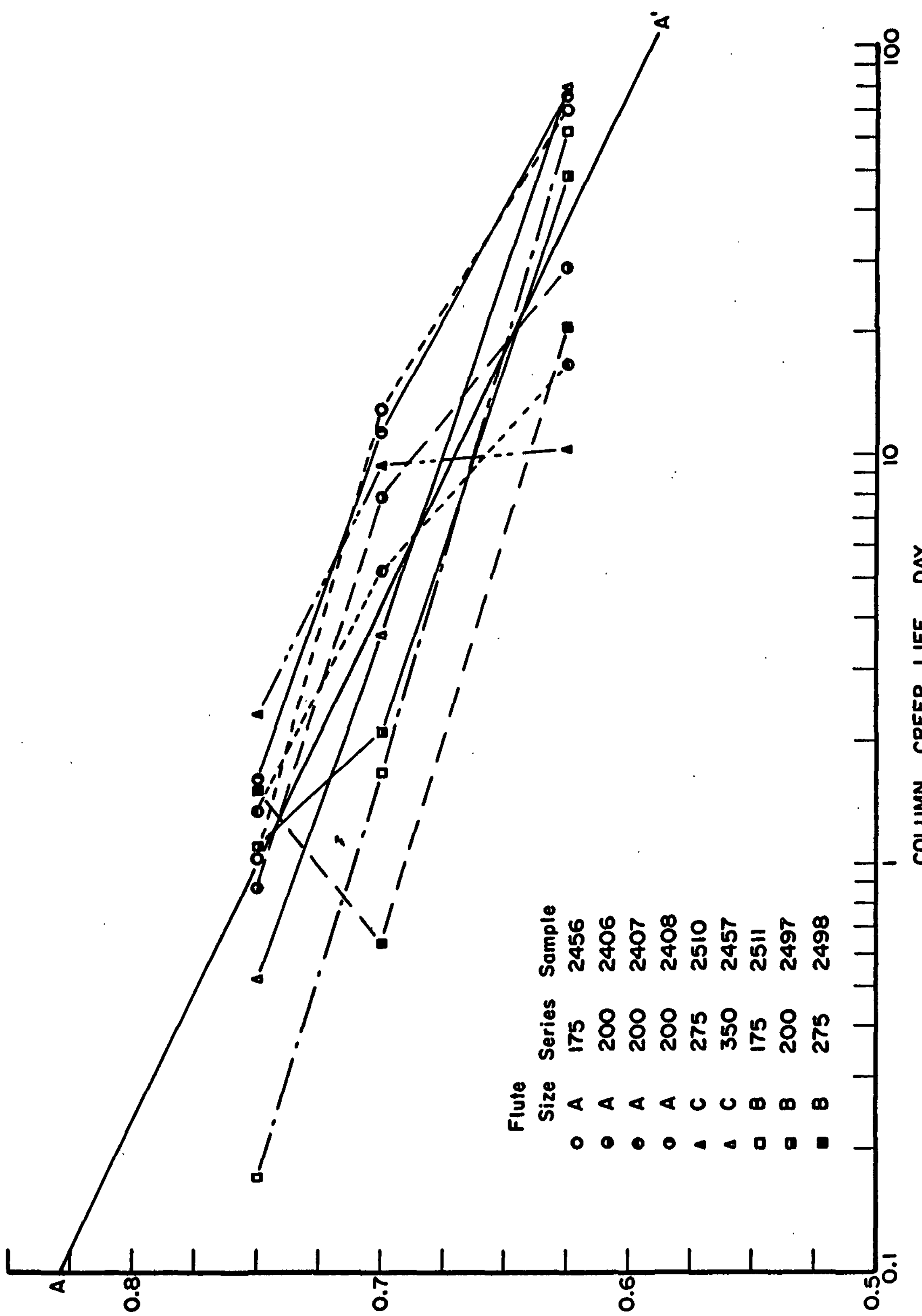

Figure 16. Relationship Between Column Creep Life and Load Ratio for Nine Samples of Combined Board

This overall trend is represented by the straight line AA' in Fig. 16, which is a regression line fitted to the totality of points. With one or two exceptions, the results for an individual sample suggest an approximately linear relationship between load and life. The most severe exception to a linear trend is Sample 2498 (B-flute, 275-lb. series) for which there is a marked inversion at $\underline{R} = 0.75$ and 0.70 where the creep life is on the order of one day.

A straight line was fit to the data for each of the nine samples. The slopes and the intercepts (at $\underline{R} = 0$) of these lines are shown in Table XI. The lines are shown in Fig. 17. An analysis of covariance revealed that the slopes of the nine regression lines are not significantly different (0.05 level) and, on the average, are equal to the slope of the overall line shown in Fig. 16*. While this does not prove that the true regression lines for all samples have the same slope, it does indicate that based on these data there is no strong reason to doubt that the lines are parallel.

On the premise that the nine lines are in fact parallel, as shown in Fig. 18, it remains that there are definite horizontal offsets among the nine samples which are statistically significant. This result indicates that the creep lives of the nine samples at a given load ratio are significantly different, in general (and this was also detected by an analysis of variance on the "unsmoothed" data at the 0.70 and 0.625 load ratios).

The horizontal offset of the lines may be measured by the intersection of the regression line with the horizontal axis, $\underline{R} = 0$, of the graph (this axis

*This and other statistical tests for column creep life are based on individual <u>specimen</u> creep life, rather than sample averages, and thereby have greater sensitivity for detecting significant differences. The 0.05 level of significance is investigated in all instances.

TABLE XI

SLOPE AND INTERCEPT OF LINEAR RELATIONSHIP BETWEEN COLUMN CREEP LIFE AND LOAD RATIO[a]

			Sample Lines			Parallel Lines	
Sample	Flute	Series	Slope, b	Intercept, log a_c	Correlation Coefficient[b]	Slope, b	Intercept, log a_c
2456	A	175	-14.265	10.8519	0.89	-12.685	9.7586
2406	A	200	-11.813	8.9325	0.81	-12.685	9.5350
2407	A	200	- 8.625	6.6489	0.79	-12.685	9.4567
2408	A	200	-13.151	10.1387	0.83	-12.685	9.8161
2510	C	275	- 4.870	4.1505	0.51	-12.685	9.5560
2457	C	350	-17.373	12.7392	0.88	-12.685	9.4967
2511	B	175	-20.530	14.6144	0.75	-12.685	9.1883
2497	B	200	-13.558	10.0573	0.84	-12.685	9.4535
2498	B	275	- 9.977	7.3306	0.54	-12.685	9.2031
Composite			-12.685	9.4965	0.23	-12.685	9.4965

[a] Equation is of the form: $\log t_c = bR + \log a_c$

where t_c = average creep life, days

R = load ratio = applied load/edgewise compression strength.

[b] Based on regression with individual specimen lives.

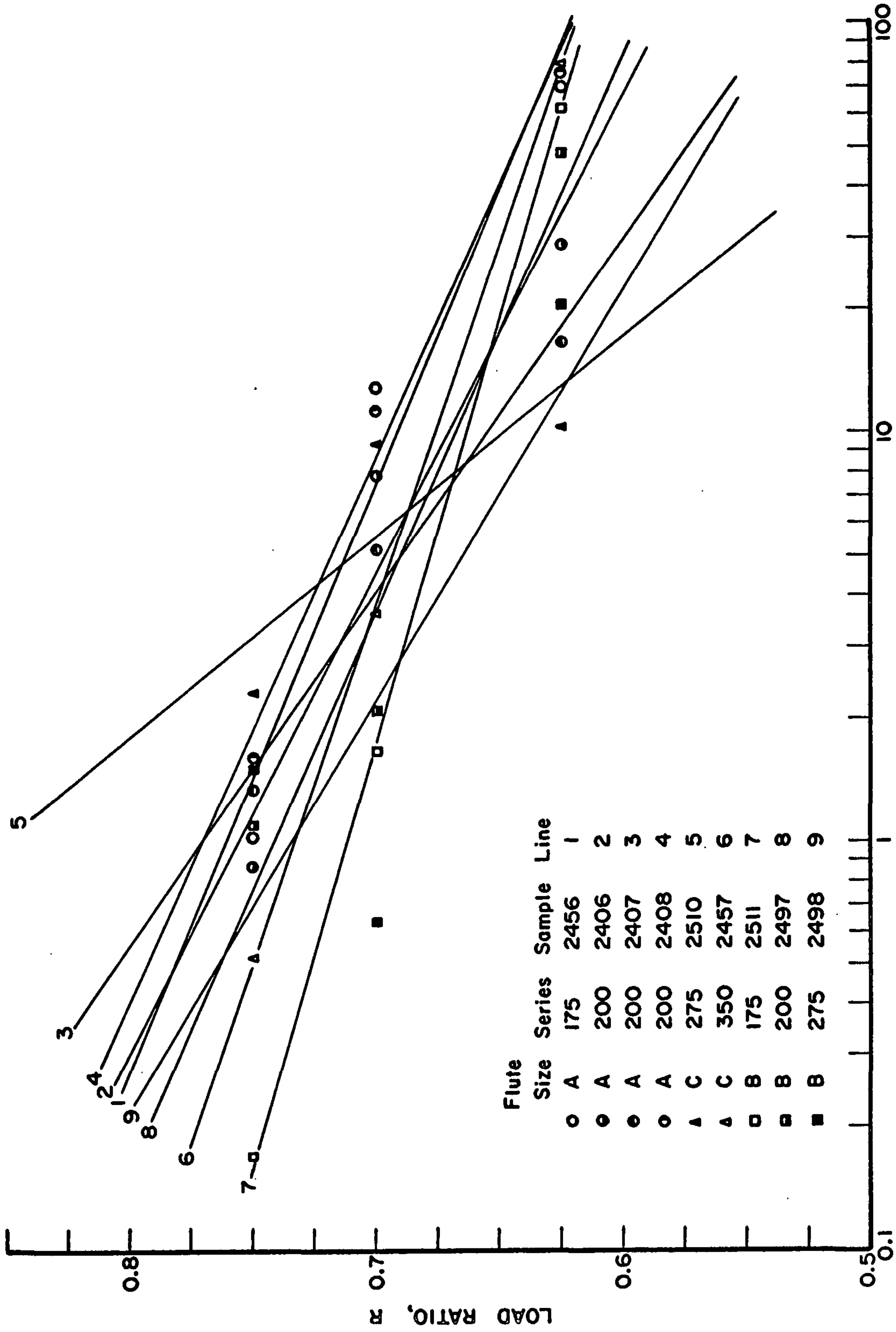

Figure 17. Linear Relationships Between Column Creep Life and Load Ratio for Nine Samples of Combined Board

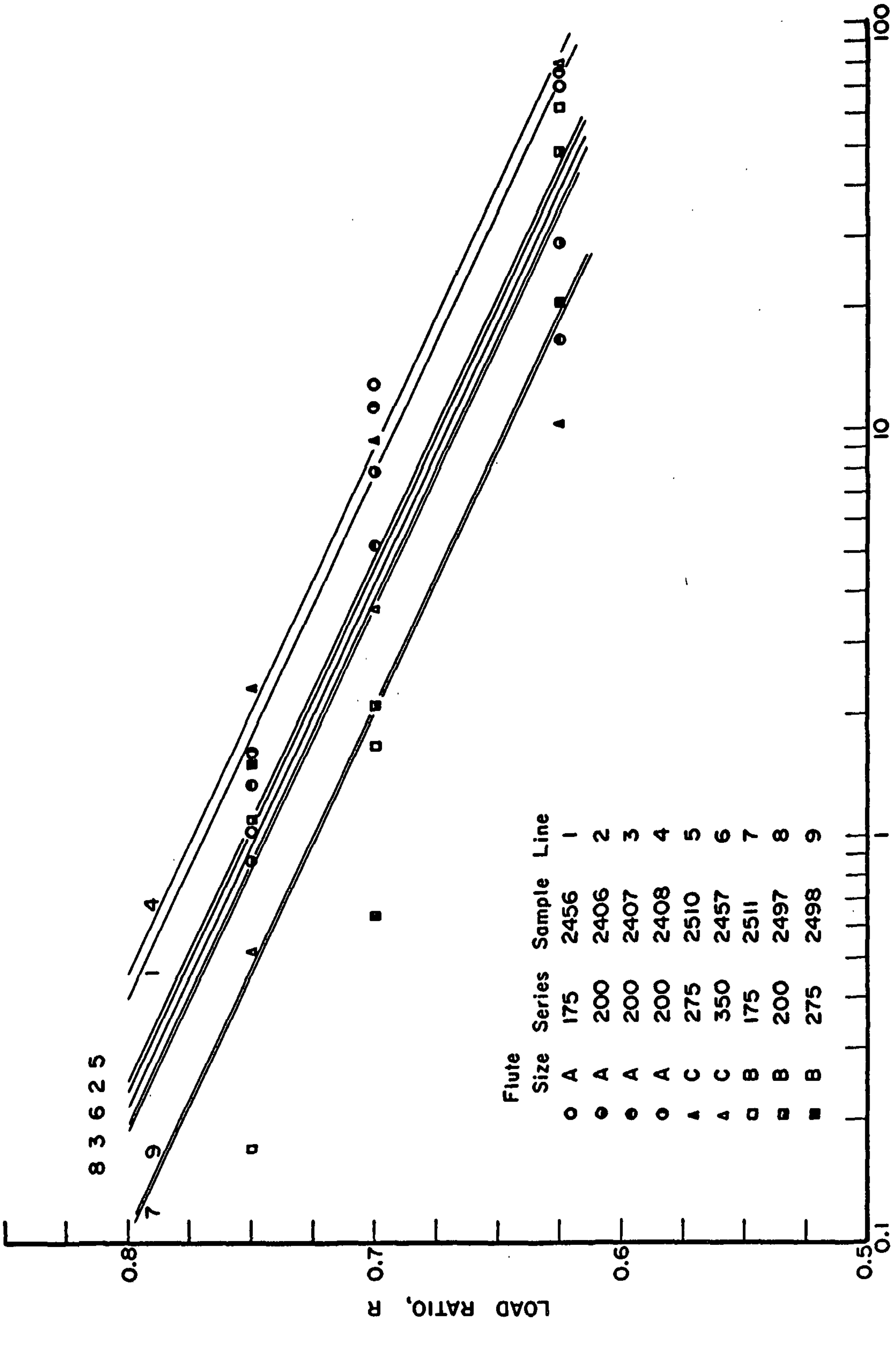

Figure 18. Parallel Line Relationships Between Column Creep Life and Load Ratio for Nine Samples of Combined Board

is not shown in Fig. 18). The intercept is termed log $\underline{a}_{\underline{c}}$ and is listed in Table XI under the heading "Parallel Lines." The difference in intercepts between two samples is, of course, the same as the horizontal offset (in logarithmic units) at any other level of $\underline{R}$. For example, the horizontal offset between the parallel lines corresponding to Samples 2456 and 2406 is 9.7586 - 9.5350 = 0.2236 in logarithmic units. This is equivalent to saying that the ratio of creep lives in units of days for the two samples is antilog (0.2236)= 1.67, on the average; that is, the creep life of Sample 2456 is 1.67 times the life of Sample 2406 at any level of $\underline{R}$. The maximum offset between any two of the nine samples is 9.8161 - 9.1883 = 0.6278 for Samples 2408 and 2511, which is equivalent to a ratio of creep lives of 4.24 at any load ratio. These two samples are A-flute, 200-lb. series and B-flute, 175-lb. series, respectively.

By way of summary up to this point, it may be stated that the average creep life (in logarithmic units) of short columns from the nine samples of combined board increased approximately linearly with decrease in load ratio in the range of this study. The data are consistent with the belief that all samples have the same rate of increase in creep life (same slope). However, the average creep life at a given load ratio varied widely between samples — by as much as a factor of four (on the basis of "smoothed" data).

It is natural to inquire whether the offset between samples in respect to the creep life relationships can be associated with some aspect of the combined board construction, for example, flute size or series. It may be recalled that similar offsets occur in box creep life curves and appear to be associated with flute size and/or other aspects of the combined board or box construction.

To examine the possible effect of flute size, a regression line was fit to the life vs. load ratio data for the four A-flute samples. Similarly, lines were fit to the C- and B-flute data. A tabulation of the slopes and intercepts of these three regression lines is given in Table XII. The slopes of the three regression lines are not significantly different and therefore the flute effect may be represented by the three parallel lines shown in Fig. 19 having a common slope of -12.685.

TABLE XII

SLOPE AND INTERCEPT OF CREEP LIFE RELATIONSHIPS ACCORDING TO FLUTE SIZE[a]

Flute	No. of Samples	Flute Regression Slope, b	Flute Regression Intercept, log a	Parallel Lines Slope, b	Parallel Lines Intercept, log a
A	4	-11.964	9.1430	-12.685	9.6416
C	2	-11.121	8.4449	-12.685	9.5264
B	3	-14.688	10.8819	-12.685	9.2817
Composite	9	-12.685	9.4965	-12.685	9.4965

[a]Relationship is of the form: $\log t_c = bR + \log a$.

In terms of the smoothed data, there are statistically significant differences (0.01 level) in the creep lives of the A-, C-, and B-flute samples of this study, on the average. Viewed as ratios, the creep life of the A-flute samples, on the average, was 2.29 times the B-flute life at a given load ratio; the C-flute average life was 1.76 times the B-flute life. Thus, for the samples at hand, A-flute combined board had longer creep life than C-flute and C-flute had longer life than B-flute, on the average.

It should be cautioned that there are relatively too few samples of board to establish this trend with certainty. Moreover, the same components were

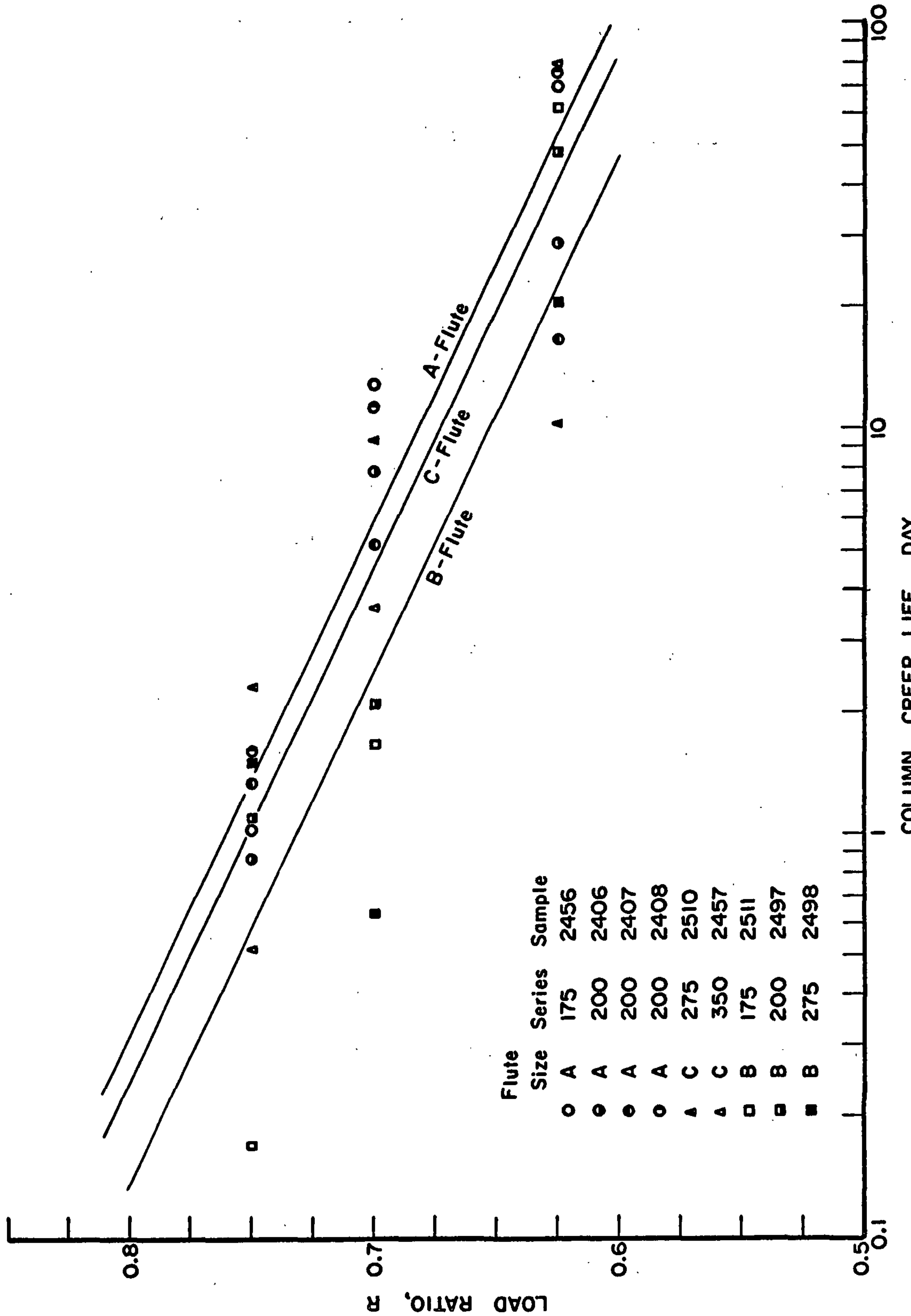

Figure 19. Parallel Line Relationships Between Column Creep Life and Load Ratio According to Flute Size

not fabricated in all flute sizes. And there is high variability between samples within a given flute size (for example, between the two C-flute samples – the "triangle" points in Fig. 19). It is possible, furthermore, that some factor other than flute size is operative (for example, fabrication variability), and is confounded with flute size in these particular samples.

One factor that may be examined in this latter regard is the type of test specimen employed in the creep test. Rectangular specimens were used in the earlier phases of testing, which involved for the most part A-flute samples. With increased testing of C- and B-flute board, however, it became apparent that it was difficult to maintain central loading of the rectangular B- and C-flute specimens because their lower caliper permitted the loading platen to "walk" to one side or the other, followed by premature collapse of the specimens. This difficulty was overcome by changing to an L-shaped (or angle) specimen; this specimen was formed by putting a vertical score (of the type used in the panel scorelines of a box) at midwidth of the specimen and then folding 90°. This type of specimen was adopted for subsequent tests of B- and C-flute board, although a number of rectangular specimens had been successfully tested in several of the samples in these flute sizes.

If there were a systematic difference between the rectangular and angle specimens in respect to creep life, it would be expected to show up in the data mainly as a difference between A-flute, on the one hand, and B- and C-flute on the other hand. However, as may be seen in Fig. 19, the greater difference in average creep life is between B- and C-flute, and relatively lesser difference between C- and A-flute. Probing deeper into the data, for those C- and B-flute samples which were evaluated by both rectangular (the successful ones) and angle specimens (see Samples 2457, 2511, 2497, and 2498 in Table X), there is no strong evidence of a systematic difference between the two types of specimens. Thus, it does not appear that the ranking of creep lives in the order A> C>B should be attributed to specimen shape.

It is not unusual for combined board behavior to be ranked in the order A>C>B or B>C>A (for example, flexural stiffness and edgewise compression) and some credence may be given to the observed trend on this basis. It is not clear at this time, however, what may be reasons for this behavior. The recognized difference between flute sizes with respect to edgewise compression strength (that is, the buckling of miniature plates of liner and medium between flute tips) should be taken care of by the presence of edgewise compression in the load ratio.

On the other hand, it may bear looking into the possibility that buckling under creep conditions introduces some further effect which may be associated with flute size. For example, edgewise compression of combined board is believed to involve the buckling of the miniature plates of components whose vertical edges are defined by the flute tips. The strength of the buckled miniature plate may be considered as depending on the edgewise compression strength of the component at and near the glue lines of the combined board and on flexural stiffness in the remainder of the miniature plate remote from the glue lines. The average stress (i.e., averaged across the caliper) of the portion of the plate primarily associated with flexure is at a lower level than the stress near the glue line. It is quite possible, therefore, that the portion of the plate which is associated with flexure creeps at a lower rate than the portion of the plate at the glue line and this would not be reflected in the short-term edgewise compression strength. A-flute board has a greater amount of the components acting in flexure than does B-flute board (with C-flute intermediate), because of the fewer number of glue lines in A-flute board. If the creep rates in flexure and edgewise compression of the components differ in the sense mentioned above, it is understandable that A-flute combined board may have a longer column creep life than B-flute board (with C-flute intermediate). This is, of course, a conjecture and points up the advisability of studying flexural creep of the components and column creep life of combined boards fabricated from the same components.

The explanation given above to explain the effect of flute size could also be applied to a box panel, the latter involving the same basic considerations of buckling and edge stress, though at a larger geometric scale. This explanation would not explain, however, the observed effect of box perimeter on box creep life and would, in fact, lead to a predicted trend in direct contradiction to the observed trend. Moreover, the explanation given earlier for the effect of box perimeter, if applied to column creep, would predict a trend contrary to that observed with respect to flute effect. Thus, the two lines of reasoning do not appear to be compatible with each other. Further study is required to determine which of these two viewpoints is an appropriate description of creep behavior of plates.

Turning attention to a possible association between creep life and series of the combined board, regression lines were fitted to the samples according to their series classification (175, 200, 275, and 350-lb.). The constants of the regression lines are shown in Table XIII. The slopes of the several lines are not significantly different and the lines are constructed parallel in Fig. 20. There is considerably less offset among these lines than was the case with classification by flute size, although the offsets are statistically significant. The maximum difference in creep life occurs between the 200 and 275 series, where the ratio of lives, on the average, is 1.53.

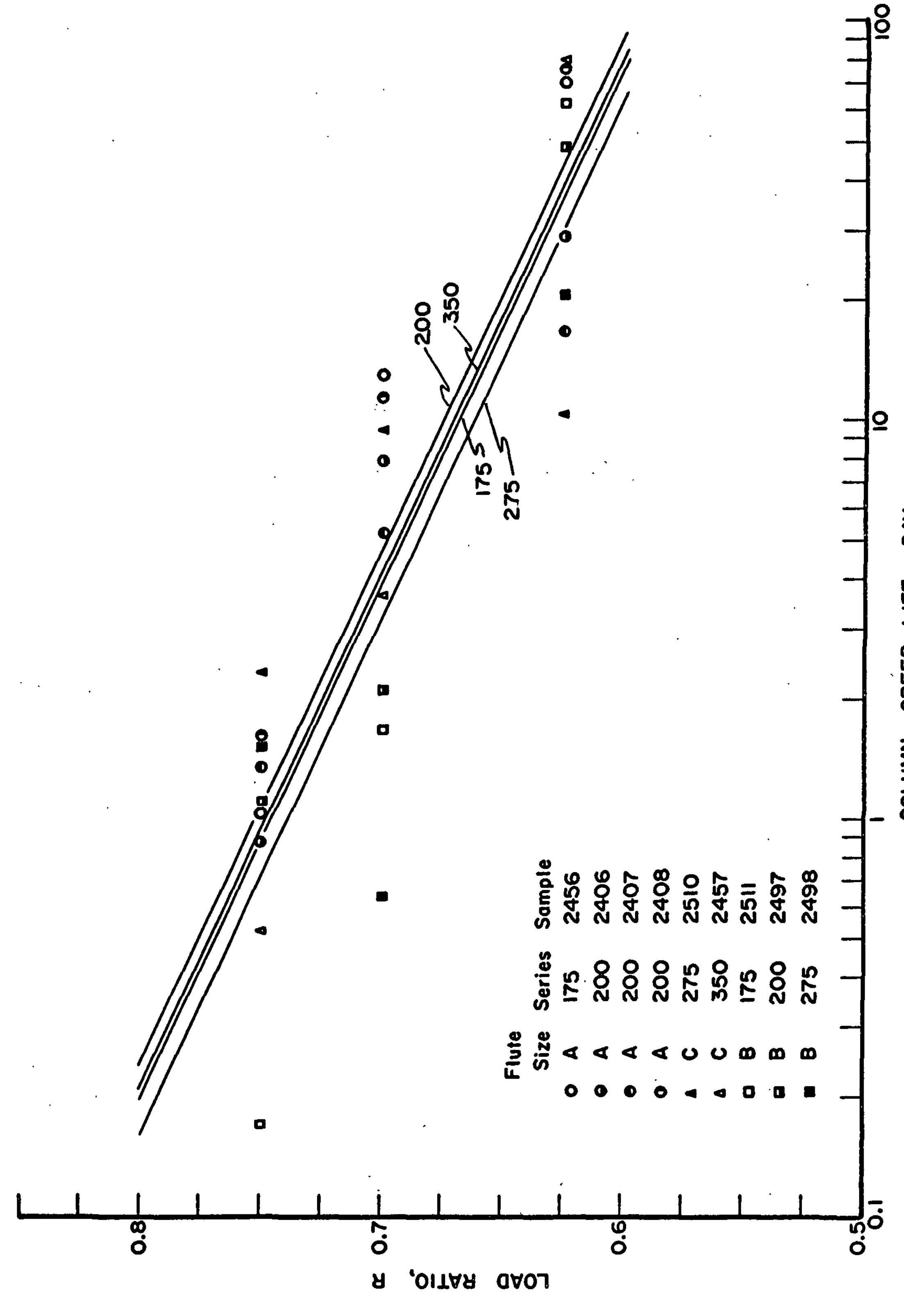

Figure 20. Parallel Line Relationships Between Column Creep Life and Load Ratio According to Series

The order of average creep life by series is 200>350>175>275. It is difficult to conceive of a physical reason for the observed ranking; if series (which mainly reflects liner weight) had an effect, it might be expected that the ranking would be in numerical order. It is believed, therefore, that what appears to be a modest effect due to series in these particular samples is really the result of some other unidentified factor, random or systematic, which merely shows up as an apparent effect due to series.

TABLE XIII

SLOPE AND INTERCEPT OF CREEP LIFE RELATIONSHIPS[a]
ACCORDING TO SERIES

Series	No. of Samples	Series Regression		Parallel Lines	
		Slope, b	Intercept, log a	Slope, b	Intercept, log a
175	2	-17.397	12.7332	-12.685	9.4735
200	4	-11.787	8.9444	-12.685	9.5654
275	2	- 7.423	5.7406	-12.685	9.3795
350	1	-17.373	12.7392	-12.685	9.4967
Composite	9	-12.685	9.4965	-12.685	9.4965

[a]Relationship of the form: $\log t_c = bR + \log a$.

By way of summary on flute and series effects, the average column creep life according to flute size was ranked in the order A > C > B, with A-flute life about 2.25 times B-flute life, and C-flute about 1.75 times B-flute. The physical mechanisms which may cause this ranking according to flute size are not clear at this time. There was a modest effect associated with series; the creep lives of the samples were ranked in the order 200>350 > 175>275. It does not seem reasonable that the lives should be ranked in this order and it is doubted that the apparent effect of series is real.

RELATIONSHIP BETWEEN BOX CREEP AND COLUMN CREEP

It may be anticipated that box creep life and column creep life are related to each other, on the grounds that the short-term compression strength of a box is intimately dependent on the edgewise compression strength of the combined board. Knowledge of the relationship between box and column creep life, if precise enough, should have utility for estimating box stacking life from creep tests of the combined board. Development of an adequate accelerated creep test of combined board would make the relationship even more useful because box performance could then be projected from relatively short duration tests of combined board in advance of box manufacture. It is conceivable that the relationships could be extended to an earlier stage of the manufacturing process, namely, component creep behavior, with corresponding advantage to the maker and user of boxes.

The relationship between box creep life and column creep life is shown in Fig. 21 for the nine samples of combined board under study. Both types of life are plotted on logarithmic scales; the plotted points are coded according to load ratio ($\underline{R}$ = 0.625, 0.70, and 0.75), and the points for a given sample of combined board are connected by line segments. There is a general trend for box life to increase with column life, as would be expected. The overall trend is represented by the regression line BB' which has the equation:

$$t_b = 8.76\ t_c^{0.743} \tag{30}$$

where $\underline{t_b}$ = time to failure of box

$\underline{t_c}$ = time to failure of column

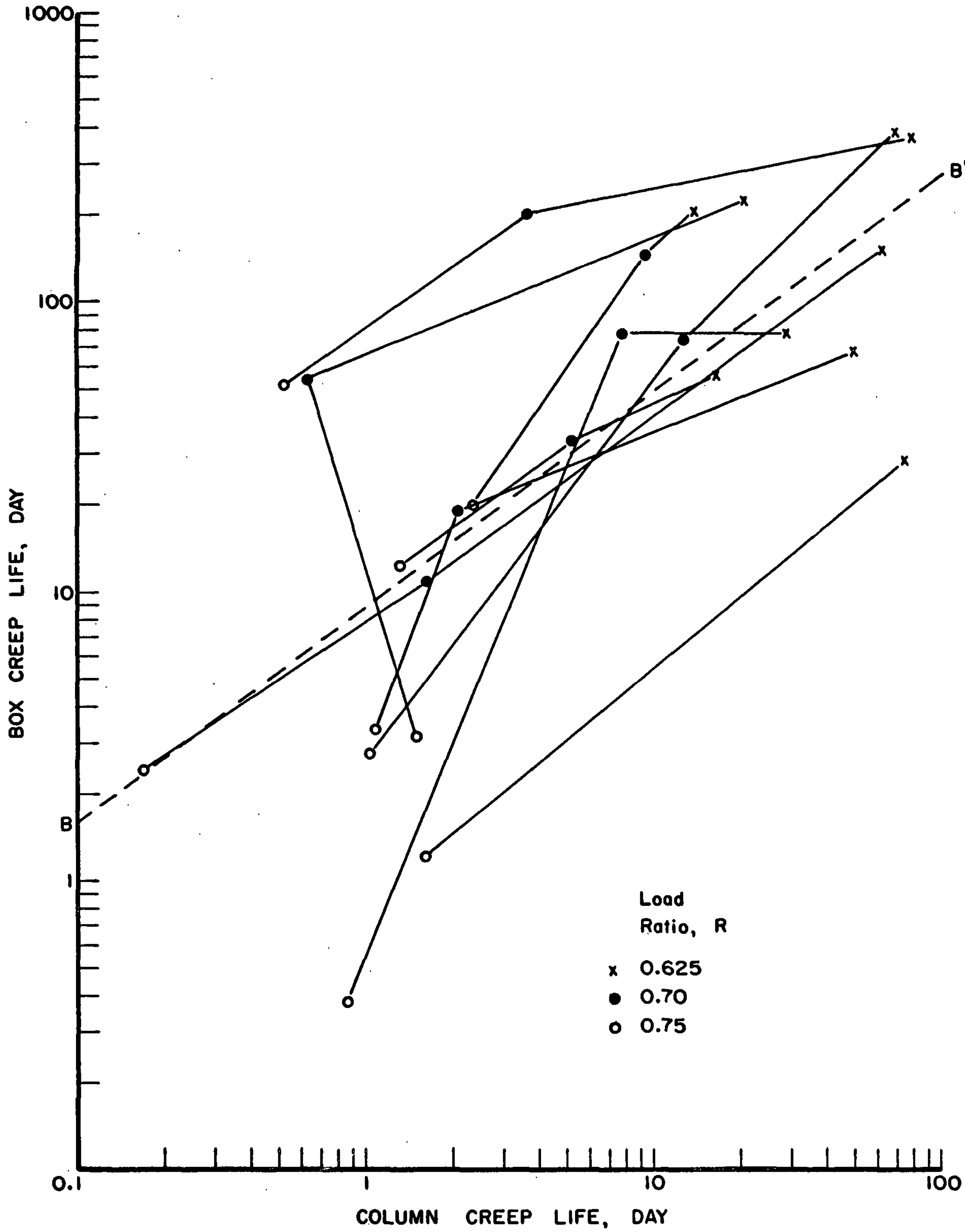

Figure 21. Relationship Between Box Creep Life and Column Creep Life for Nine Samples of Combined Board

There are, however, several prominent inversions or near-inversions in the data, some of which are traceable to aforementioned inversions in the column data and others to the box data.

It may also be noted that box life is generally greater than column life at a given load ratio. A number of the box lives (average) exceed 100 days while none of the column lives (average) exceeds 100 days. Based on the overall relationship (line BB'), box life is 9 days when column life is one day, and box life is 270 days when column life is 100 days.

The differing order of magnitude between box and column life may be attributed to the box being a more complex structure than the column. Although a portion of the box may be disposed to fail (say, one panel or a portion of one panel), the remainder of the box may survive for some greater period of time. On the other hand, the column, being a simpler structure, may be expected to fail catastrophically once the critical point is reached. Moreover, the nature of the column tester is such that it determines the shorter of the creep lives of two specimens; when one of the two specimens fails, the upper platen of the tester tilts and induces collapse of the other specimen. Thus, the short column creep test leads to a somewhat lower estimate of column life than if the same number of specimens had been tested individually.

In view of the approximately linear relationship between box and column life (in logarithmic units) in several of the samples, a straight line was fit to the data for each sample with the results shown in Table XIV. The constant, log $\underline{c}$, in the equation is the logarithm of box life corresponding to a column life of one day; (any other value of column life could equally well have been selected). The several slopes $\underline{b}$ are not significantly different and therefore

TABLE XIV

LINEAR RELATIONSHIP[a] BETWEEN BOX AND COLUMN CREEP LIVES ACCORDING TO COMBINED BOARD SAMPLE

			Sample Lines		Parallel Lines	
Sample	Flute	Series	Slope, b	Constant, log c	Slope, b	Constant, log c
2456	A	175	1.1806	0.4637	0.7988	0.8396
2406	A	200	1.6106	-0.1043	0.7988	0.5135
2407	A	200	0.5993	1.0366	0.7988	0.9004
2408	A	200	0.8203	-0.0883	0.7988	-0.0660
2510	C	275	1.4782	0.7619	0.7988	1.2934
2457	C	350	0.3705	1.9220	0.7988	1.6129
2511	B	175	0.6970	0.9042	0.7988	0.8619
2497	B	200	0.6697	0.7549	0.7988	0.6671
2498	B	275	0.6906	1.2267	0.7988	1.1802
Composite			0.7433	0.9423	0.7988	0.9029

[a] Equation is of the form: $\log t_b = b \log t_c + \log c$

or equivalently $t_b = c\, t_c^{\,b}$

where t_b = box creep life at a given load ratio R

t_c = column creep life at same load ratio.

the box-column relationships may reasonably be expressed by parallel lines with a common slope of 0.7988, as indicated in Table XIV and shown graphically in Fig. 22. It should be remarked that the significance test for slopes is not very sensitive in this instance because of the small number of points per sample and hence relatively few degrees of freedom; consequently, differences in slope would have to be large to be declared significant. As in the previous discussion of column life, parallel slopes for the several samples must be regarded as an assumption (not contradicted by the data) rather than a proved fact.

The vertical offset between the parallel lines is statistically significant and indicates that there are real differences in the creep lives of the nine samples of boxes when the combined boards have the same column creep life. There are a number of factors which conceivably may govern box creep life in addition to (or other than) column creep life. Among these are: panel dimensions, flap scorelines, manufacturer's joint, etc. None of these factors can possibly be reflected in the short column creep test. Moreover, box creep may depend on flexural stiffness of combined board. On the strength of the relationships evident in Fig. 21 and 22, it seems improbable that column creep life is unrelated to box life; however, the vertical offsets suggest that some additional factor(s) is operative. Lacking a theory for creep buckling of box panels and lacking creep life data for combined board other than short columns, an attempt is made in the following to determine whether or not any of the several "gross" aspects of box construction can be associated with the vertical offset of the box-column creep relationships.

Figure 23 is a graph of box vs. column life according to flute size. That is, a straight line was fit to the A-flute data collectively, and similarly

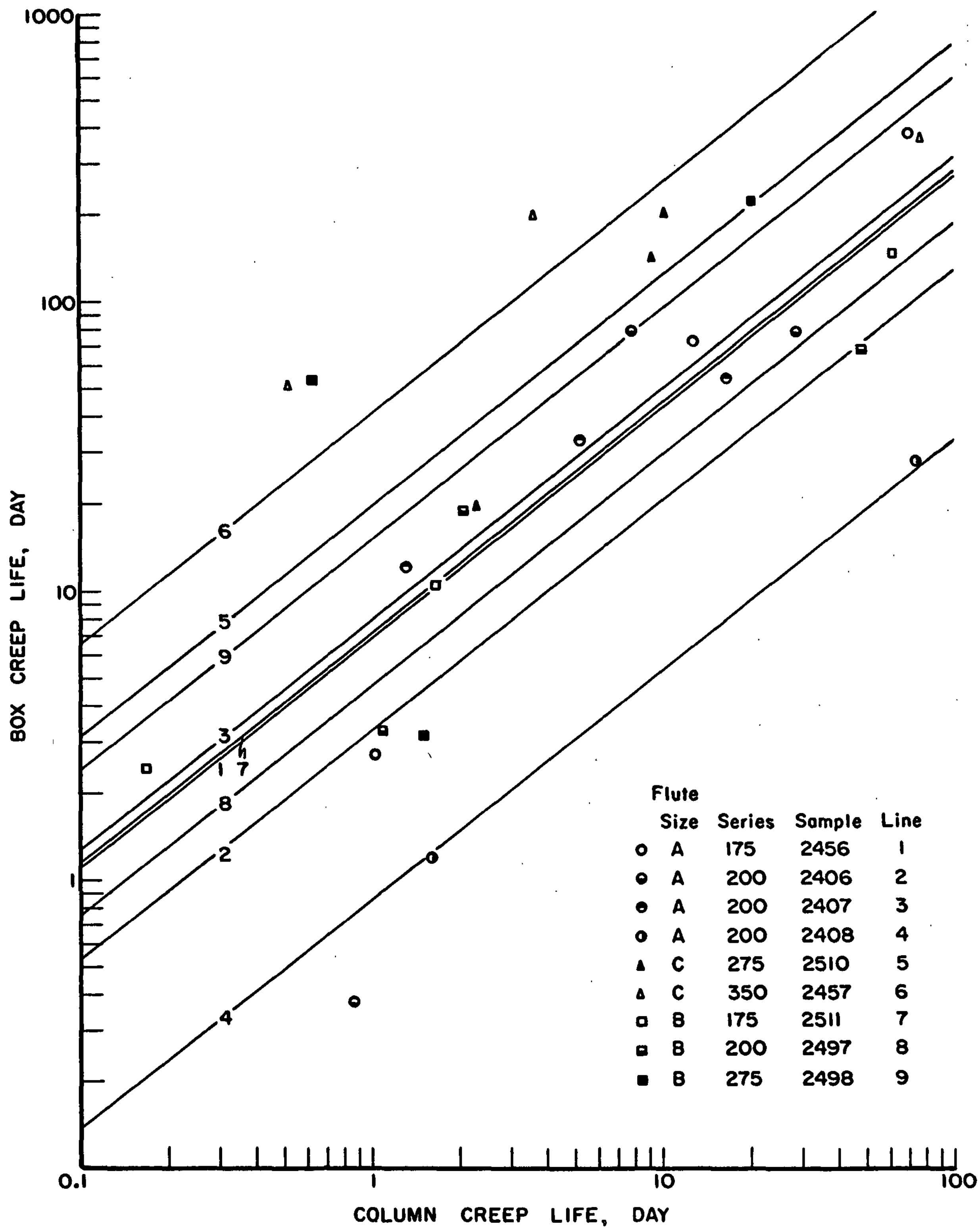

Figure 22. Parallel Line Relationships Between Box Creep Life and Column Creep Life for Nine Samples of Combined Board

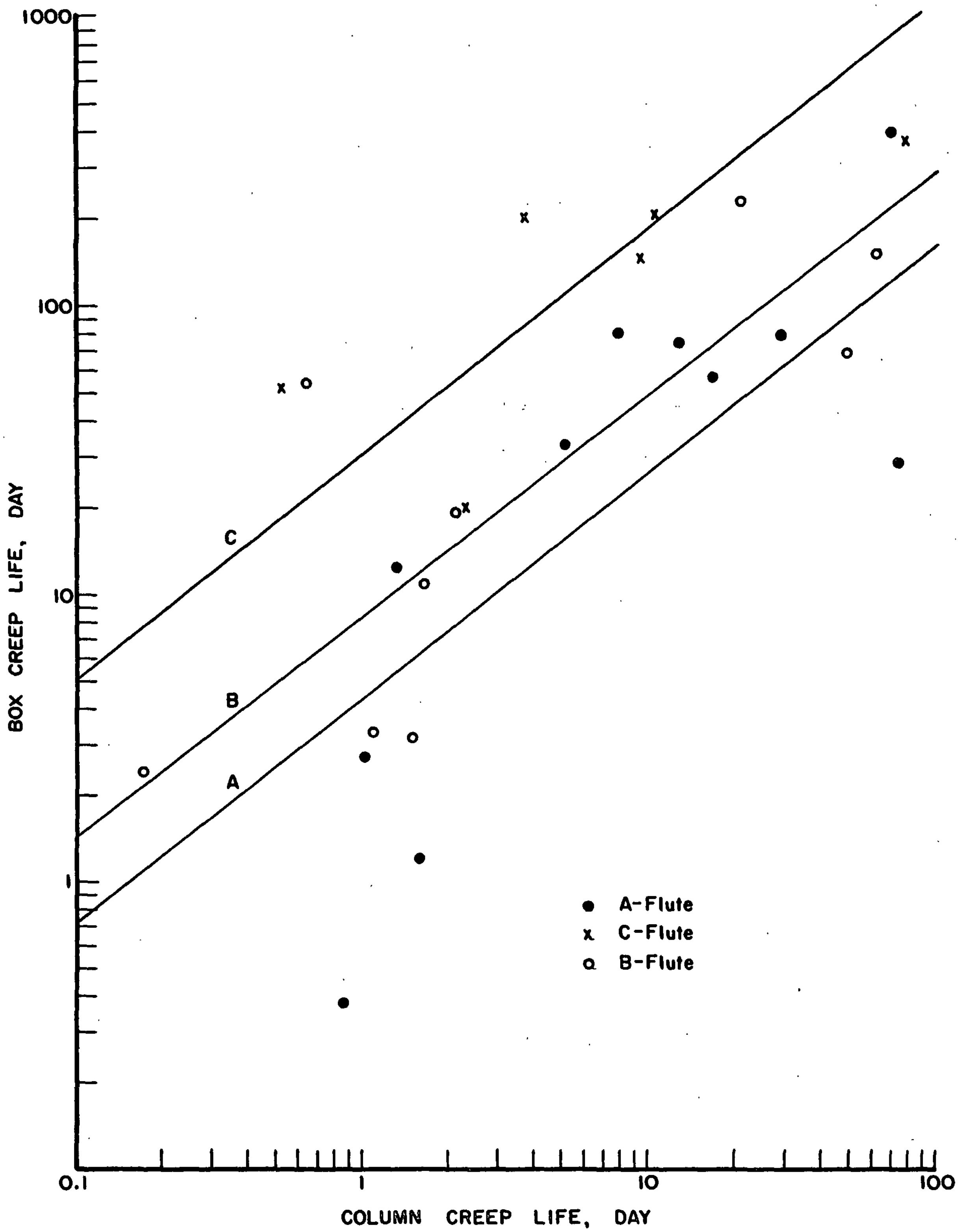

Figure 23. Parallel Line Relationships Between Box Creep Life and Column Creep Life According to Flute Size

for B- and C-flute. The constants of the regression lines are listed in Table XV. The slopes of the three lines do not differ significantly, and therefore, three parallel lines are shown in Fig. 23. It is seen that there is substantial (and significant) vertical offset between A-, B- and C-flute, hinting that flute size may be a factor in box life in addition to column life. However, the box lives are ranked in an unfamiliar order of C>B>A for a given column life. This ranking is unfamiliar in the sense that all known mechanical behavior of combined board leads to the ordering A>C> B or B>C>A; only the trivial ranking by alphabet, which is historical rather than mechanical, agrees with the observed rank in Fig. 23. It is questionable, therefore, whether or not flute size per se is a factor (along with column life) governing box life. Quite possibly some other factor is in truth responsible and is intermingled or confounded with flute size in this particular small collection of samples. Further test experience, preferably with A-, B-, and C-flute boards fabricated from the same components, would be helpful to confidently resolve this question.

Figure 24 is a graph of the data according to series, which is essentially according to liner weight. The constants are tabulated in Table XVI; again the slopes are not significantly different between series, while the vertical offsets between the resulting parallel lines are significant. The data imply that, in general, heavyweight boards lead to higher box life than lightweight boards for a given column creep life; it may be conjectured that flexure creep life is involved in this trend (and the same might be said in respect to the possible effect of flute size). There is, however, one serious inversion in the trend, namely, that the average life of the two 175-series samples is greater than the average of the four 200-series samples. This inversion detracts considerably from the

TABLE XV

LINEAR RELATIONSHIP[a] BETWEEN BOX AND COLUMN CREEP LIVES ACCORDING TO FLUTE SIZE

Flute	No. of Samples	Flute Regression: Slope, b	Flute Regression: Constant, log c	Parallel Lines: Slope, b	Parallel Lines: Constant, log c
A	4	1.0410	0.3968	0.7642	0.6320
C	2	0.4711	1.6996	0.7642	1.4792
B	3	0.6631	0.9721	0.7642	0.9207
Composite	9	0.7433	0.9423	0.7642	0.9274

[a] Equation is of form: $\log t_b = b \log t_c + \log c$.

TABLE XVI

LINEAR RELATIONSHIP[a] BETWEEN BOX AND COLUMN CREEP LIVES ACCORDING TO SERIES

Series	No. of Samples	Series Regression: Slope, b	Series Regression: Constant, log c	Parallel Lines: Slope, b	Parallel Lines: Constant, log c
175	2	0.8514	0.8140	0.7705	0.8706
200	4	0.8433	0.5214	0.7705	0.5773
275	2	0.8617	1.1987	0.7705	1.2540
350	1	0.3705	1.9220	0.7705	1.6333
Composite	9	0.7433	0.9423	0.7705	0.9230

[a] Equation is of form: $\log t_b = b \log t_c + \log c$.

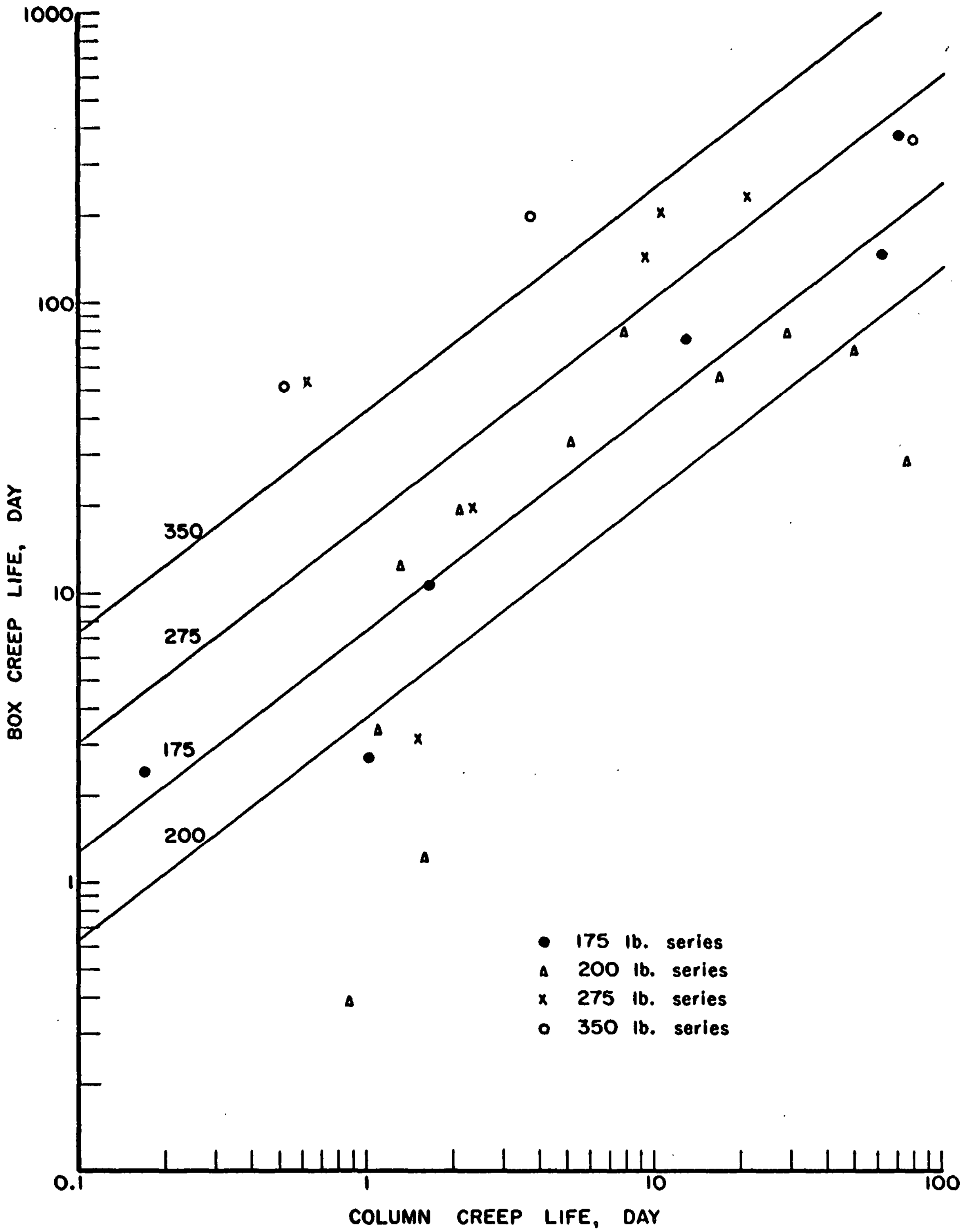

Figure 24. Parallel Line Relationships Between Box Creep Life and Column Creep Life According to Series

credibility of the series effect and, accordingly, series can perhaps at best be regarded as a possible factor in box life (along with column life).

The data were also examined with respect to box dimensions to determine whether this factor may be associated with the offset of the box life vs. creep life relationships evident in Fig. 22. The samples are listed in the order of increasing perimeter of the box in the first three columns of Table XVII. The vertical positioning of each sample line in Fig. 22 is measured by log c (from Table XIV). A graph of the relationship between log c and perimeter is given in Fig. 25. Despite considerable scatter there is some indication of a trend for log c to decrease with increasing perimeter, although this trend hinges mainly on the result for the largest perimeter box. There is also a suggestion in the graph that some factor in addition to perimeter may influence log c since the nine points seem to fall into two groups. Thus, there is no clear indication in the data that the offsets of the box vs. column life relationships depend in a simple way on box perimeter.

Similar classifications of the samples were made with respect of length-to-width ratio (L/W), box depth (d), and depth-to-perimeter ratio (d/Z) which relates to buckling of the box panels. The relationships between log c and these factors are shown in Table XVII and Fig. 25 and 26. Depth (d) and d/Z both reveal a fairly good correlation with log c except for one or two highly deviant points in each case. These trends are compatible with results given earlier in this report, namely, that box creep life appears to depend on load ratio, edgewise compression, and a depth effect. In the present discussion, load ratio and edgewise compression are effectively combined into column creep life, with the result that box life may depend on column life and depth of the box. The reason for increasing life with increasing depth is not clear.

TABLE XVII

EFFECT OF BOX DIMENSIONS ON OFFSET OF COLUMN VS. BOX CREEP RELATIONSHIP

Sample	Perimeter, Z in.	log c[a]	Sample	Length/Width, L/W	log c[a]	Sample	Depth, d, in.	log c[a]	Sample	Depth/Perimeter, d/Z	log c[a]
2456	39.74	0.8396	2408	1.00	-0.0660	2406	9.5	0.5135	2406	0.168	0.5135
2457	49.00	1.6129	2457	1.00	1.6129	2498	11.4	1.1802	2498	0.168	1.1802
2497	51.26	0.6671	2498	1.12	1.1802	2497	11.8	0.6671	2408	0.202	-0.0660
2511	51.50	0.8619	2407	1.20	0.9004	2456	12.5	0.8396	2497	0.230	0.6671
2510	56.00	1.2934	2406	1.31	0.5135	2511	14.4	0.8619	2407	0.247	0.9004
2406	56.50	0.5135	2510	1.33	1.2934	2510	18.5	1.2934	2511	0.280	0.8619
2498	67.76	1.1802	2497	1.50	0.6671	2407	19.0	0.9004	2456	0.315	0.8396
2407	77.00	0.9004	2511	1.51	0.8619	2408	19.0	-0.0660	2510	0.330	1.2934
2408	94.00	-0.0660	2456	2.00	0.8396	2457	19.8	1.6129	2457	0.404	1.6129

[a] From Table XIV, Parallel Lines.

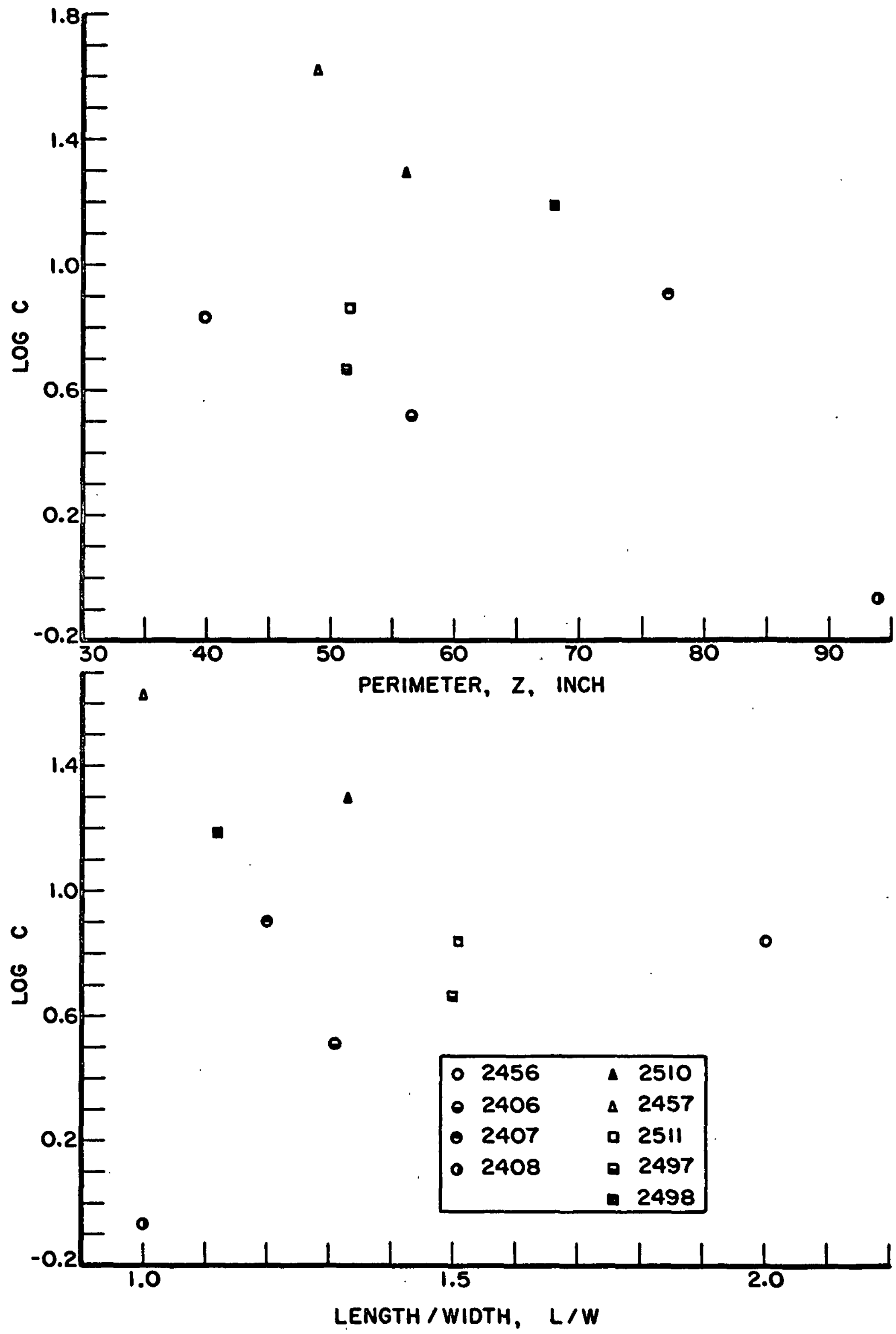

Figure 25. Relationship Between Log c (Box Life at a Column Life of 1 Day) and (a) Perimeter and (b) Length-to-Width Ratio

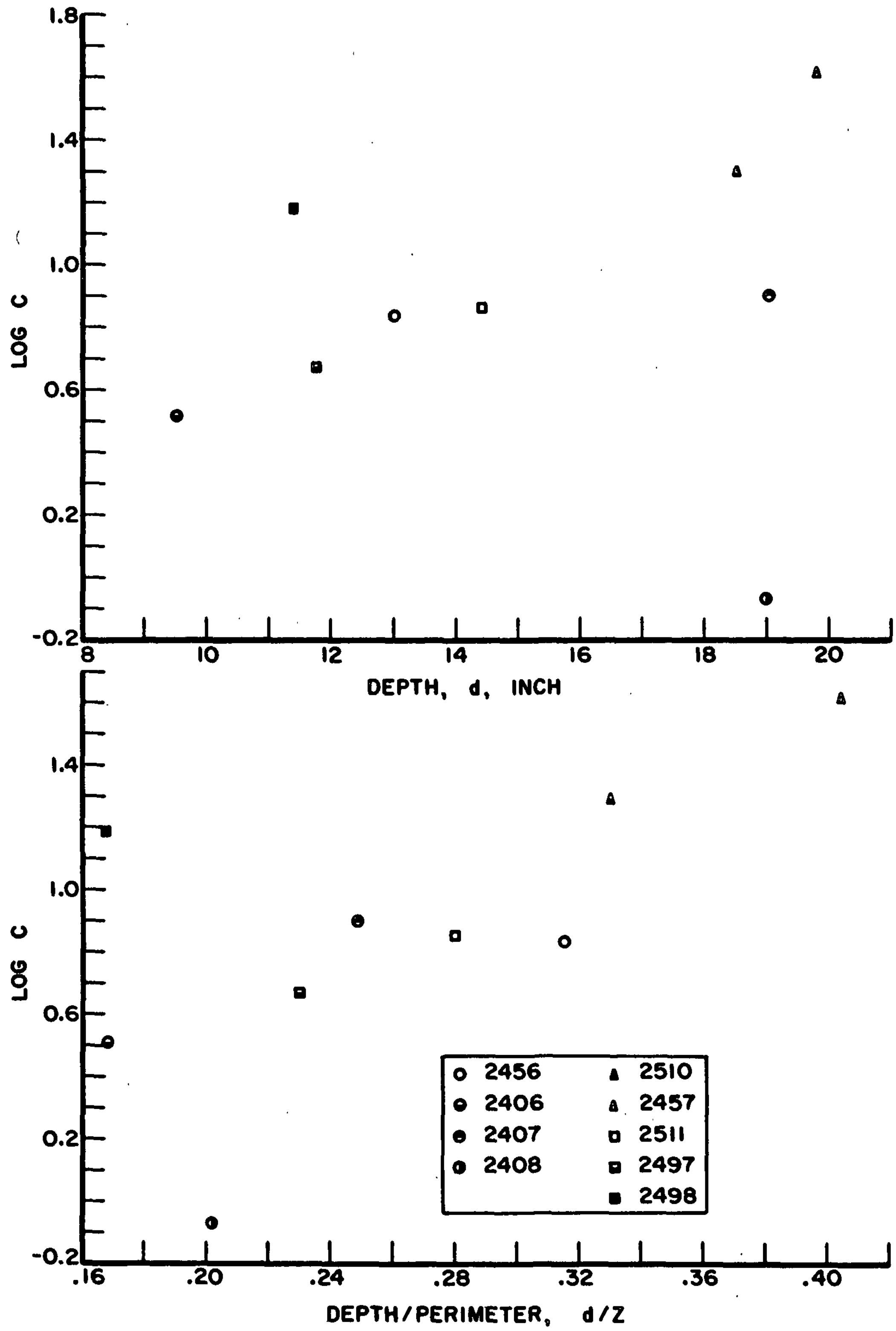

Figure 26. Relationship Between Log c (Box Life at a Column Life of 1 Day) and (a) Depth and (b) Depth-to-Perimeter Ratio

Another way of examining the box vs. column creep life relationship is in terms of the offset of the box life vs. load ratio curves for the nine samples and the offset of the creep life vs. load ratio curves for the samples. That is, the correlation between the box life intercept, log a_b, and the column life intercept, log a_c, may be studied. If these intercepts have high positive correlation, it implies that the same factor(s) probably affects both box life and column life and that this factor is a material property of combined board rather than some aspect of box construction. On the other hand, a low degree of correlation implies that additional and/or different factors govern box life than govern column life.

To pursue this approach, log a_b and log a_c from Appendix, Table XIX, and Table XI, respectively, (parallel line fit) are plotted as a correlation diagram in Fig. 27. It may be seen that there is no evidence of a correlation between the two intercepts for these nine samples or within a flute size or within a series. It is concluded, therefore, that whatever factors may affect creep life in addition to load ratio, these factors are probably different for columns and boxes. Stated another way, some box construction factor(s), rather than solely combined board properties, probably governs box creep life along with column creep.

In summary, box creep life and column creep life (at the same load ratio) were only roughly proportional. In general, box life exceeded column life by a factor of about 3 to 10, on the average. For a given column life, there was considerable variation in box life among the nine samples of combined board. There was no strong evidence that the differences in box life (at a given column life) were associated with flute size, series or box dimensions with the

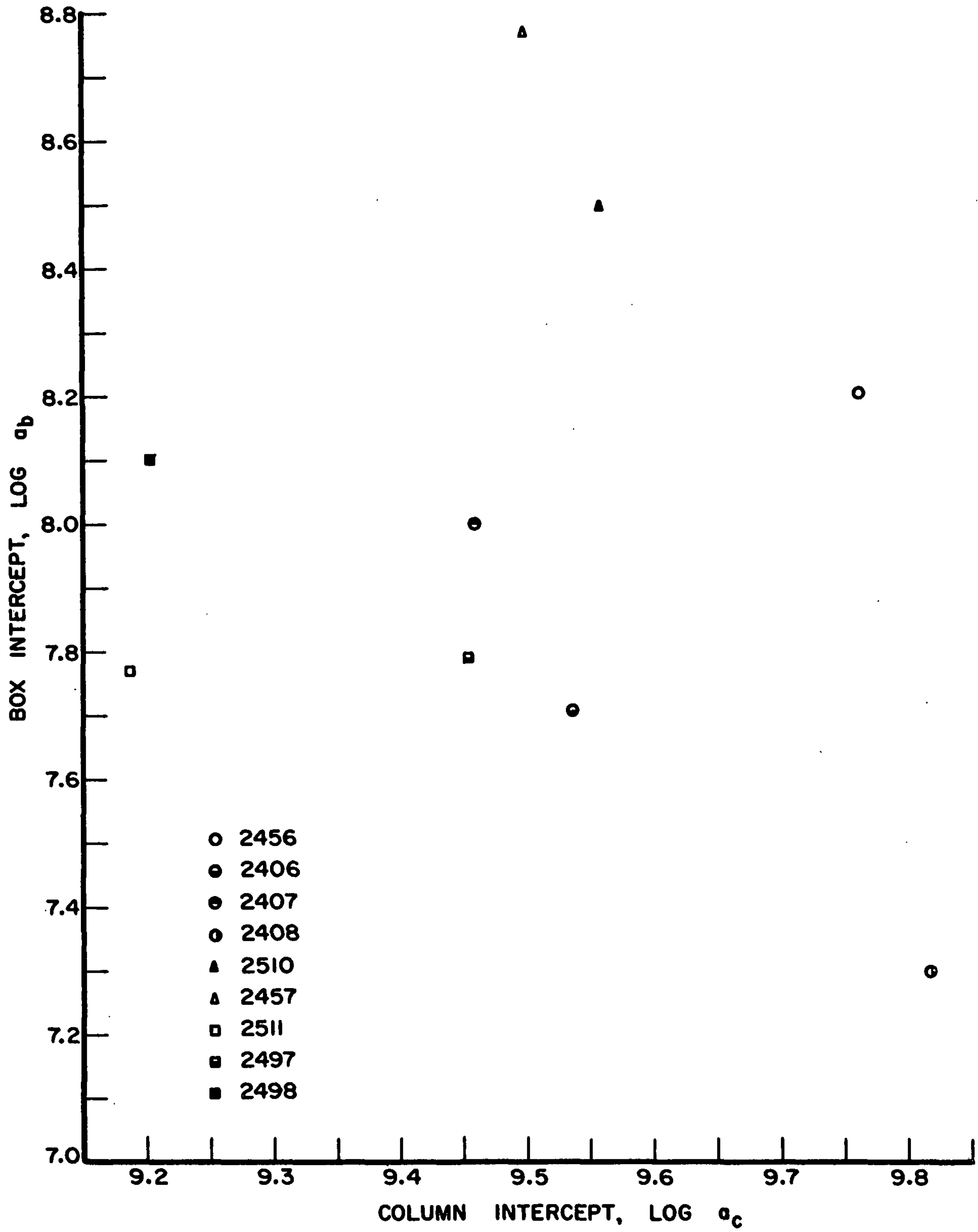

Figure 27. Relationship Between Log $\underline{a}_b$ and Log $\underline{a}_c$

possible exception that depth or depth-to-perimeter ratio may be important. Column creep life appears to depend on some combined board property in addition to load ratio. Box creep life appears to depend on one or more box construction factors in addition to column creep life.

LITERATURE CITED

1. Garofalo, F. Fundamentals of creep and creep-rupture in metals. New York, The MacMillan Co., 1965.

2. Lubahn, J. D., and Felgar, R. P. Plasticity and creep of metals. New York, J. Wiley and Sons, Inc., 1961.

3. Odqvist, F. K. G. Mathematical theory of creep and creep rupture. London, Oxford University Press, 1966.

4. Alfrey, T., Jr. Mechanical behavior of high polymers. New York, Interscience, 1948.

5. Brezinski, J. P., Tappi 39, no. 2:116-28(Feb., 1956).

6. Clouser, W. S. Forest Products Laboratory Report No. 2150, Sept., 1959.

7. Rance, H. F., Paper Makers' Assoc. Gt. Brit. Ireland, Proc. Tech. Sect. 29:449-69(1948).

8. Rance, H. F. In Merideth's Mechanical properties of wood and paper. Amsterdam, North-Holland Pub. Co., 1953. 298 p.

9. Jacobsen, P. M. H., World's Paper Trade Rev. 134:150, 152, 155-6(1950).

10. Cheung, H. C., Textile Res. J. 34, no. 7:597-604(July, 1964).

11. Busse, W. F., Lessig, E. T., Loughborough, D. L., and Larrick, L., J. Appl. Phys. 13:715-24(1942).

12. Kellicutt, K. Q., and Landt, E. F., Fiber Containers 36, no. 9:28, 30, 35-6, 38(Sept., 1951).

13. Kellicutt, K. Q., Tappi 46, no. 1:151-4A(Jan., 1963).

14. Brynhildsen, H. O., and Dagel, Y., Svensk Papperstid. 62, no. 3:77-82 (Feb. 15, 1959).

15. Wolf, M., Package Eng. 7, no. 11:60-3(Nov., 1962).

16. Stott, R. A., Appita 13, no. 2:84-8, discn.:89(Sept., 1959).

17. Moody, R. C., and Skidmore, K. E., Package Eng. 11, no. 8:75-81(Aug., 1966).

18. Hoff, N. J. Wilbur Wright Memorial Lecture. J. Roy. Aero Soc. 58:31(1954).

19. McKee, R. C., Gander, J. W., and Wachuta, J. R., Pbd. Pkg. 48, no. 8:149-59 (Aug., 1963).

20. Hoff, N. J. A survey of the theories of creep buckling. AFOSR TN 50-382 Stanford Univ. Dep't. Aero Engng. no. 80. June, 1958. 60 p.

21. Hoff, N. J. Structures and materials for finite lifetime. Proceedings of the First International Congress of the Aeronautical Sciences, Advances in Aeronautical Sciences, Vol. 2. London, Pergamon Press, 1959.

22. Gerard, G., J. Aerospace Sci. 29. no. 9:1087-90(Sept., 1962).

23. Papirno, R., and Gerard, G., J. AIAA 1, no. 9:2127-33(Sept., 1963).

24. The Institute of Paper Chemistry. Compression strength formula for corrugated boxes. TESTING, Compression Report 79, Sept. 10, 1963.

25. Dixon, W. J., and Massey, F. J. Introduction to statistical analysis. 2nd ed. p. 209-19. New York, McGraw-Hill, 1957.

THE INSTITUTE OF PAPER CHEMISTRY

W J Whitsitt

W. J. Whitsitt
Research Associate
Container Section

J. W. Gander

J. W. Gander
Research Associate
Container Section

R C McKee

R. C. McKee
Chairman
Container Section

APPENDIX

TABLE XVIII

RESULTS FOR BOXES UNDER TEST BETWEEN AUGUST 1 AND NOVEMBER 15, 1966

Sample No.	Load Ratio, R	Survival Time, days	Deflection, inch
2406	0.575	Over 585	0.69[a]
2407	0.675	Over 247	0.67[a]
2407	0.575	Over 585	0.68[a]
2408	0.550	Over 575	0.82[a]
2430	0.700	292.4	0.64
2456	0.575	Over 765	0.47[a]
2456	0.575	Over 585	0.44[a]
2456	0.550	769.9	0.53
2456	0.550	Over 865	0.45[a]
2457	0.700	Over 463	0.98[a]
2457	0.700	Over 244	0.97[a]
2457	0.625	Over 864	0.96[a]
2457	0.575	Over 765	0.94[a]
2497	0.575	Over 455	0.42[a]
2498	0.575	Over 775	0.53[a]
2510	0.700	Over 244	0.47[a]
2510	0.700	99.1	0.46
2510	0.625	Over 172	0.45[a]
2510	0.625	Over 159	0.44[a]
2510	0.575	Over 454	0.51[a]

[a]Failure not reached; deflection reading just prior to removal of load.

Note: Tests discontinued on November 15, 1966.

TABLE XIX

COVARIANCE REGRESSION LINE CONSTANTS FOR BOX RESULTS

Sample No.	Log a[a]	Estimated Values of Failure Time, days	
		R = 0.625	R = 0.75
2406	7.70658	57.9	3.75
2407	8.00538	115.2	7.46
2408	7.29972	22.7	1.47
2456	8.20375	182.0	11.8
2457	8.76718	665.9	43.1
2497	7.78815	69.9	4.52
2498	8.10102	143.6	9.30
2510	8.49608	356.7	23.1
2511	7.77132	67.2	4.35
Composite	7.99521	112.6	7.29

[a] Regression form $\log t = \log a - 9.51R$.

TABLE XX

COVARIANCE TESTS OF RELATIONSHIP BETWEEN R AND BOX STACKING LIFE

Type of Significance Test	Log of Individual Values			Logarithmic Averages			Log of Arithmetic Averages		
	F	D.F.	Significance Level	F	D.F.	Significance Level	F	D.F.	Significance Level
1. Difference in sample means adjusted for R	6.82	8,110	0.01	3.24	8,22	0.025	3.20	8,22	0.025
2. Test of single regression line	4.88	16,102	0.01	2.02	16,14	N.S.	1.91	16,14	N.S.
3. Differences between slopes of sample regression lines	2.30	8,102	0.025	0.910	8,14	N.S.	0.823	8,14	N.S.
4. Linearity of regression	5.82	7,110	0.01	2.887	7,22	0.05	2.91	7,22	0.05

Note: N.S. = Not significant at 0.05 level.